

# **Investigation of pressure drop characteristics of coal slurry pipeline**

**A  
Thesis**

*submitted in partial fulfillment of the requirements for the award of degree of*

**Master of Engineering (M.E.)**

**In  
Thermal Engineering**

**Submitted by  
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## CERTIFICATION

I, Mohit Bhayana, declare that this thesis report entitled "*Investigation of pressure drop characteristics of coal slurry pipeline*", submitted towards fulfillment of the requirements for the award of Master's Degree in Thermal Engineering, in Mechanical Engineering Department of Thapar University, Patiala, is entirely my own work. This document has not been submitted for any degree in any other institution.

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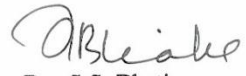
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## **ABSTRACT**

Transportation of coal through pipeline is advantageous in terms of many factors like less operating and capital cost, more reliable than any other modes of transport. The present work of experimentation of coal water slurry flow through pilot plant test loop is conducted at Thapar University, Patiala. The effect of varying input concentration of solids at 3%, 7% and 10% on pressure drop is studied on sudden contraction and pipe bend geometries at different flow rates. The physical and chemical characteristics coal sample with respect to its hydraulic transportation through pipeline is studied. The numerical investigation is also carried out using commercial computational fluid dynamics code FLUENT to study the pressure drop at various pipe transitions. The numerical simulation results of pressure drop for coal slurry flowing through the bend is compared with the published literature and is found to be in good agreement. The pressure drop is determined both experimentally as well as numerically at different concentrations 3%, 7% and 10% by varying the discharge and the comparison is made. It is found that there is a little deviation between the experimental and numerical results. The pipe fitting geometries like sudden contraction and bend were simulated for analysing the coal slurry flow behaviour at high concentration of 40%, 50% and 60%. The pH characteristics of coal slurry with increasing concentration of solids by weight was studied and it was found that the slurry pH decreases with increasing concentration of solids by weight.

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<b>NOMENCLEATURE</b>	
<b>I<sub>m</sub></b>	Hydraulic gradient
<b>S<sub>s</sub></b>	Solids to fluid density ratio
<b>C<sub>vd</sub></b>	Delivered concentration by volume
<b>ρ<sub>f</sub></b>	Fluid density
<b>g</b>	Accerlation due to gravity in m/sec <sup>2</sup>
<b>J<sub>m</sub></b>	Pressure gradient for the mixture
<b>ρ<sub>m</sub></b>	Mixture density (Kg/m <sup>3</sup> )
<b>C<sub>s</sub></b>	Solids concentration
<b>C<sub>w</sub></b>	Concentration of solid by weight
<b>ρ<sub>s</sub></b>	Solids density
<b>W<sub>s</sub></b>	Solids weight
<b>W<sub>w</sub></b>	Weight of water in slurry
<b>V<sub>c</sub></b>	Critical velocity
<b>S</b>	Specific gravity of substance
<b>D</b>	Pipe diameter in mm
<b>C<sub>o</sub></b>	Output concentration of solids
<b>C<sub>i</sub></b>	Input concentration of solids
<b>d<sub>50</sub></b>	Median particle diameter
<b>SG<sub>apparent</sub></b>	Apparent specific gravity
<b>SG<sub>true</sub></b>	True specific gravity
<b>Ø</b>	Porosity
<b>ρ<sub>bulk</sub></b>	Bulk density of a substance
<b>ρ<sub>particle</sub></b>	Particle density of a substance
<b>U, v, w</b>	Velocities in x, y and z directions
<b>μ</b>	Molecular viscosity coefficient

$\Upsilon$	Second viscosity coefficient
$f_x$	Body force component in x direction
$k$	Turbulent kinetic energy per unit mass
$\epsilon$	Dissipation rate of turbulent kinetic energy for unit mass
$\mu_t$	Turbulent dynamic viscosity
$G_k$	Turbulence kinetic energy due to mean velocity gradient
$G_b$	Turbulence kinetic energy due to buoyancy
$\Upsilon_m$	Contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate
$S_k$	Source term
$C_{1s}, C_{2s}$	Model constants
$\sigma_\epsilon$	Prandtl number

Transporting the solid using carrier fluid like water or oil through pipeline is a very old process. Many organisations have been working in the field of slurry transport system since 1960's. The transportation of fuel like coal and disposal of coal ash in the form of slurry through pipeline is a safe process in terms of causing environmental hazards.

The main difficulty in using the coal at thermal power station is the non-availability of effective transport means from coal mines to distant located power stations. Transportation of solid by truck and rail is a costly process, consuming lots of energy and causes environment problems. The system of delivering solid through pipeline will be economical in comparison to other means of transport. For the long stretches, pipes need more volume of slurry and water which will increase the effective cost over the distance.

Slurry transportation system comprises up the following elements. These are the basic elements needed for the transportation of slurry.

- Water supply system
- Coal preparation plant
- Coal slurry pipelines and pumping elements
- Coal dewatering plants

Since the thermal power stations are located at far distant away from mines, the technology such as Capsule Pipeline has been emerged to transport the coal and certain bulk materials from mine to power sector. Capsule Pipeline involves two variations having different carrier fluids to transport the coal. One of them is Coal Log Pipeline (CLP) where the coal is transported hydraulically using water and another is Pneumatic Pipeline where the coal transports pneumatically using air.

A number of industries such as chemical and waste disposal industries have been using this technology for transporting the solids. While transporting the slurry we face up many problems relating to the design of slurry pipeline. There are many factors that certainly affect the slurry

transportation phenomenon through pipeline. But, before going up further, in order to investigate the parameters affecting slurry transport, it is necessary that first we clearly understand the theory behind the slurry transportation system.

## **1.1 SLURRY**

It is generally defined as fluid mixtures of solids having its powder form with a carrier fluid like water or oil. It is like a thick fluid, flowing under the action of gravity and being able to move forward by means of pumping action. The physical attributes of coal slurry depends upon many factors such as particle size distribution (PSD), amount of solid present in liquid phase taken in either by volume or by weight, turbulence present in mixture during conveyance, mixture temperature, size of conduit and viscosity of the carrier fluid like water. Oil, water, air and many other fluids are used as the carrier fluids for transporting the solid from one place to others. Slurry is basically treated as a two phase flow mixture which must overcome the critical velocity in order to avoid the settling in pipeline. The speed of the slurry flow must be sufficiently high so that the solid particulates can remain suspended. Coal slurry is basically characterized by a number of attributes like particles size, water content, amount of ash, viscosity, flow ability etc. As the slurry flows through the pipe, the following types of mixture are formed inside the pipe network.

## **1.2 TYPES OF SLURRY**

Depending upon the characteristics of fluid and solid particulates, the flow of slurry is generally classified into the following categories:

- Non-Settling slurry
- Settling slurry

### **➤ Non-Settling Slurry**

In this kind of slurry particles are in suspension for a long time. The size of particles in the non-settling slurry is generally less than 40  $\mu\text{m}$ . Viscosity of the non-settling slurry affects mainly by the solids concentration taken in either by weight or by volume. As the solids concentration

increase, viscosity also increases with it. Increase in particle concentration leads to the increase of non-newtonian nature of slurry.

➤ **Settling Slurry**

Here, the particles will be falling and settling at the bottom of the container where the particles are kept. The particles get settled down when their size is found above than 40µm.

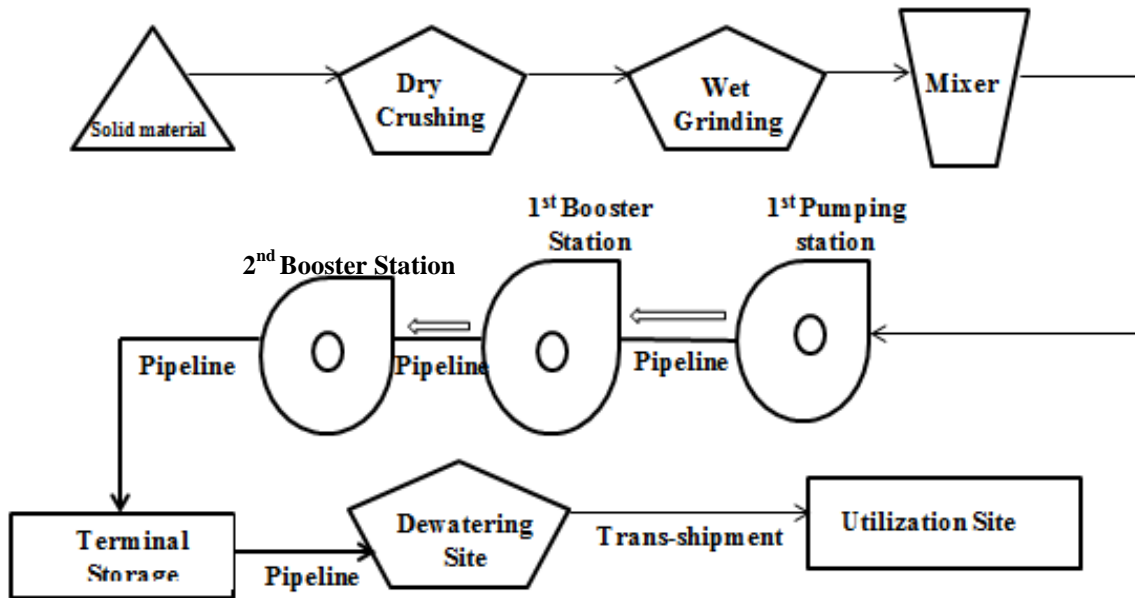
Based upon the settlement criterion, the wide ranges of particle size and their nature are available:

<b>Particle size range</b>	<b>Nature</b>
40 µm to 200 µm	Small (Suspensions)
200 µm to 2 mm	Medium (Transition)
2 mm to 5 mm	Large (heterogeneous)
5 mm to greater than 200mm	Very large (heterogeneous)

### **1.3 HYDRAULIC CONVEYING OF SOLIDS**

It involves the conveyance of solid particulates under suspension through the moving fluid. A number of slurry pipelines have been constructed in order to carry out mineral particles through water. Very high tonnage, over haul transportation of coal and various other minerals like iron, limestone in hydraulic pipelines is now a booming commercial substitute as compared to other ways of bulk solids transport vehicles like railway trains, Lorries and barges.

Figure 1.1 shows the basic schematic diagram of hydraulic conveyance of solids through pipelines. Firstly, a large amount of solid is kept on preparing in such a manner that it may pass through different sizing stages as the stage of reducing the size by doing grinding and milling upon it and then followed by the next stage of mixing with water. After completing the process of slurry preparation, slurry is then placed in storage tanks and keeps on agitating the solid particles with in the suspension, before pumping through the pipeline. Depending upon the pipeline length, a few number of pumping stations may be required at intermediate points. At the receiver's end, it is usually necessary to remove all the carrying liquid from the solid in the 'de-watering plant' before being used as a fuel at thermal station.



**Figure 1.1 Hydraulic Conveying of Solids**

## **1.4 COAL SLURRY THROUGH PIPELINE**

It is seen that Indian coal consists of the lesser heating value and higher ash content but has less environment effects in terms of creating less pollution. It has contained low amount of sulphur and non-existence of heavy metals such as mercury, arsenic, lead, selenium and cadmium. Coal pipelines are basically used to transport the coal from the coal mining area to power project area where the power being developed. Trucks are being used for a small distance and rail lines are preferable for long distances. Basically, there are two types of coal pipelines. First, one of them is slurry pipeline which is using a mixture of pulverized coal and water. The ratio of coal and water to be taken is in the ratio of 1:1 and that ratio may be taken in the varying amount. It can be varied up to 3 or 4 to 1. Before using the coal at thermal plant, it must be dried. Coal transported as slurry requires a lot of drying and amounts to less electricity. To dry the coal, water is evaporated continuously. Water is used to transport the coal especially in arid regions like the south western United States. The hurdles coming in using the indigenous coal throughout the country is the non-availability of transport linkages from coal mines to power plants. There is a shortage of trains that can carry the coal freight as well. While transporting the coal it is ensured that the slurry being pumped at a minimum velocity of 6 feet per second. It is done in

such a way that the settling of coal can be prevented at the bottom of the pipe. Fewer pumping stations are needed to employ along the length of the pipeline. In India, Coal reserves are mainly located in central regions of the country.

Coal can be transported to any place in India with a maximum slurry pipeline length of 1500 Km. About Rs. 800 per ton of coal is the present day cost of transporting the coal across the length of 1500 Km. It is reported that one metre diameter pipe can transport a minimum amount of 30 million tons of dry coal which is subjected to 8000 MW capacity power generation. The encouragement of this project in our country will definitely control all the coal fired projects irrespective of their locations. This project is useful at those areas where the coal is first converted into powder form. Firstly, the slurry pipeline concept was issued in 1891 and the first coal slurry pilot plant was built in a vacant lot at 58<sup>th</sup> street and Madison Avenue in New York City. The first ever usage of coal slurry pipeline was made by England in 1914 which was used to transport coal from the Thames River docks into London. America waited for 1957 to come to adopt the first commercial coal slurry line.

## **1.5 TYPES OF COAL SLURRY PIPELINE**

Till today, the two major alternatives for the transportation of coal from mine to the thermal power plant have been searched out

- Wet transportation of Coal
- Dry transportation of Coal

### **1.5.1 Wet transportation of Coal**

The transportation of coal is seen as a highly environmental sensitive issue. Wet disposal of coal is meant to the transportation of coal being done with the help of moving fluid like water through the pipeline to the pond.

➤ **Classification of Wet transportation**

• **Low Concentration Slurry Pipeline (LCSP)**

The concentration of solid particulates in mixture lies in the range of 10 to 30 % taken by weight.

➤ **Advantages**

- Smooth flow of slurry through pipeline.
- Simple centrifugal slurry pumps are required to transport the coal.
- Operating cost is less also in comparison to other modes of transport.

➤ **Disadvantages**

- A lot of drying is required which results in a large amount of energy consumption for drying purposes.
- Quantity of water consumes more while transporting the coal at low concentration.

➤ **Medium Concentration Slurry Pipeline (MCSP)**

The concentration of solid particulates in the mixture lies within the range of 40 to 50% by weight.

➤ **Advantages**

- The simple centrifugal slurry pumps having few modifications can be used during handling of the medium concentration slurry.
- As more amount of slurry handled at a time results in a less number of pumps required at a time.
- Quantity of water is also decreased.

- Ground water and air pollution both are reduced considerably.
- Wear rate of the pipe also reduces effectively with using the medium concentration slurry and amount of ash transported through pipe increases.
- Specific power consumption required for the transportation also reduces with this system.

➤ **Disadvantages**

- A very tight control on parameters like concentration of solid, grain size is required so that the flow ability could maintain.
- Although, much theory is available over this disposal system but still experience of field is mandatory before implementation.

➤ **High Concentration Slurry Pipeline (HCSP)**

Herewith, the concentration of solid particulates rises up and reaches up to 60% by weight. Special types of pumps like Reciprocating, Diaphragm and Progressive type pumps are used for transporting the high concentration slurry through the pipe network.

➤ **Advantages**

- The consumption of water is very much less as compared to previous ones.
- A very less amount of energy is needed for drying purposes because the disposal system has ability of self-setting.
- Specific power consumption is much less than other wet disposal systems.
- Pipeline diameters and transportation velocities can also be reduced considerably which results in less wear of the pipe.

➤ **Disadvantages**

- Initial investment is high during the installation of special purpose pumps.
- Highly efficient control of parameters is necessary.

### **1.5.2 Dry transportation of coal**

In this transportation system the coal transports by means of truck and conveyor. The limitation of this system is that the system takes a large investment to install in comparison to wet disposal system.

## **1.6 FACTORS AFFECTING THE SLURRY TRANSPORTATION THROUGH PIPELINE**

While transporting the solid particulates by means of carrier fluid like water through pipeline, the number of forces acts upon the mixture and due to which the fluid flow loses its energy. After predicting the factors which are affecting the slurry flow, there will surely be an improvement in the models like pressure losses due to friction, optimum velocity. The following factors are discussed below which basically govern the fluid flow through pipeline.

- Specific energy consumption
- Hydraulic gradient
- Solid concentration
- Critical velocity
- Critical deposit velocity

- Transport efficiency
- Hold up
- **Specific energy consumption**

The operating condition of slurry is primarily governed by the energy requirement. It is basically the amount of energy consumed in transporting the one kg mass across the pipeline length of one metre and it can be written mathematically as:

$$\mathbf{SEC} = \frac{I_m}{S_s C_{vd}} \quad (1.1)$$

El-Nahas et al. (2009) consumption of specific energy finds to increase with the increase in concentration of solid either by weight or by volume. That's why the hydraulic transportation of slurry in dense phase is considered in terms of efficiency and economy.

➤ **Hydraulic gradient**

It is defined as the head loss due to friction relative to height of fluid with the help of which slurry maintaining its ability to flow continuously. Thus mathematically can be written as:

$$\mathbf{I}_m = \frac{1}{\rho_f g} \left( -\frac{\Delta p}{\Delta x} \right) \quad (1.2)$$

Where  $-\frac{\Delta p}{\Delta x}$  the pressure drop for a unit length of pipe. But on the other hand one more term available is pressure gradient which is proportional to the density of the mixture in such a way that the height of column of slurry rises for the unit length of pipe. Hence mathematically such as

$$\mathbf{J}_m = \frac{1}{\rho_m g} \left( -\frac{\Delta p}{\Delta x} \right) \quad (1.3)$$

Where  $J_m$  is the pressure gradient and  $\rho_m$  is the density of mixture which is given by as

$$\rho_m = \rho_s C_s + \rho_f (1 - C_s) \quad (1.4)$$

➤ **Solid Concentration**

The amount of solid particles presents in carrier fluid like water or oil taken either by weight or volume. The energy required for transporting the solids hydraulically strongly depends upon the solid concentration. Nowadays, the main hurdle in slurry transportation through pipeline is, transporting the solids at high concentration. The physical phenomenon such as wear rate is related to the concentration as wear rate of pipe increases with increasing volumetric concentration due to increasing particle-particle interactions and their wall collisions.

➤ **Critical Velocity**

A number of researches have been done in order to find an exact definition for flows of fluids but still it is under investigation. It is basically the transport velocity in case of homogenous flow of slurry considering both regimes of carrier fluid as laminar or turbulent. On the other hand it is the deposit velocity in case of heterogeneous flow of slurry.

➤ **Critical deposit velocity**

Durand et al (1953) found the empirical correlation in order to predict velocity of deposition of particles in slurry. It is basically the velocity of slurry below which the deposition or settling occurs inside the pipe. The empirical correlation for calculating critical deposit velocity is discussed as

$$V_c = F_L \sqrt{2gD(s - 1)} \quad (1.5)$$

The term  $F_L$  is a dimensionless term and function of diameter of particle which depends upon the average size of particle and solid concentration.

➤ **Transport efficiency**

The efficiency of transport is the ratio of coming out concentration from the pipeline to the going in concentration to the pipeline for a unit volume of the material. Hence mathematically can be written as

$$\eta = \frac{C_o}{C_i} \times 100 \% \quad (1.6)$$

The efficiency of transport is inversely proportional to the input concentration in a manner that the increase in input concentration leads to decrease in efficiency of transport. With increase in mixture velocity, the efficiency of transport is found to increase. Grain size also affects the solid transport efficiency in such a manner that always using the fine size of grains in order to increase the efficiency of transport.

➤ **Hold up**

While fluid flowing through pipeline, fluid flow mainly consists of several layers which move with different velocity in such a manner that fluid layer adjacent to the pipe wall, moves slower than others due to the phenomenon of slip takes place. Hold ups are produced due to slip and consequently delivered concentration goes on decreasing as compared to in situ concentration.

## 1.7 INSTALLED SLURRY PIPELINE PROJECTS IN INDIA

There are so many pipelines available in India working for the transportation of Iron ore as a transported material through pipeline. Some of them are listed below.

<b>Location</b>	<b>Pipe length (Km)</b>	<b>Working Organization</b>	<b>Capacity (Mt/yr)</b>
Kudremukh - Mangalore	68	KIOCL	8
Kirandul- Vishakhapatnam	267	Essar steel	8
Barbil- kalinganagar	230	BRPL	4
Joda-paradip	253	Essar steel	8

## **1.8 NEED OF STUDY**

The demand of coal is increasing day by day for both steel plants as well as for power plants. For the transportation of ultrafine concentrate used at thermal power plant, the special type of wagons will be required. This problem could be avoided with the use of hydraulic transportation of coal slurry through pipeline. It is the best way to transport the solid material having unidirectional traffic only. It has minimum losses, easier river crossings and many other advantages. The hydraulic conveyance of solid has now been accepted as a feasible alternative to the modes of transportation. A number of slurry pipelines have been working in India since few years back but still the research is going on in the field of hydraulic conveyance of solid through pipeline. In this regard, factors affecting the slurry transport such as particle size, pressure drop characteristics, critical velocity and deposition velocity are still needed to analyse in a better way so that the consumption of energy could be minimised. The motivation of the present work is to note down the pressure drop across the pipe loop by conducting experiment and then analysing the results by doing simulation for the coal slurry flow using Computational Fluid Dynamics (CFD).

A number of researchers have been studied on flow characteristics of slurry from the last so many years. This Chapter is useful in reviewing the different papers dealing with the flow characteristics of slurry. The focus of the present study is mostly on the study of pressure drop characteristics of coal slurry flowing through the test loop being taken at varying concentration across the pipe length.

### **2.1 FLOW CHARACTERISTICS OF SLURRY THROUGH PIPELINE**

**Schaanet al. (2000)** studied experimentally the effect of particle shape on pipeline friction by taking the two pipeline testing loops having the pipe diameters of 50 mm and 150 mm for turbulent flow. They studied three sets of particles namely Ottawa sand, Lane Mountain sand and Glass beads at solids concentration ranging from 15 to 45% having the major difference of particle shape only. They defined a term as circularity for the shape of particles. This term was defined 1 for the spherical shape of particles. Three particles of different circularities to be as 0.893, 0.709 and 0.618 were considered to analyze the effect of particle shape. The Pressure gradients were measured with the help of differential pressure transducer and Bulk velocities were measured with calibrated magnetic flux flow meters along with digital computers were employed to monitor the transducer and flow meter output voltages. It was seen that pipeline friction increases with the angularity of particles as the pressure drop observes to be more in lane mountain sand than others due to more angularity present in lane mountain sand.

**Gillies et al. (2004)** studied experimentally the flow of heterogeneous slurries of sand having the median diameter of as 0.09 mm and 0.27 mm in a laboratory test pipeline of dimension 0.103 m in diameter at volume fraction of solid from 0.19 to 0.33 and flow velocity ranging from 0 to 8 m/sec. The pressure drops were measured with the help of calibrated transducers and velocities were measured with a magnetic flux flow meter. They observed that the pipeline friction gets lower down than the expected at high velocities of slurries of sand. A new correlation for particle shape factor was also proposed.

**Verma et al. (2006)** experimentally studied the pressure drop characteristics for the flow of fly ash slurry at high concentration through 90° horizontal bend. They employed a pipe loop of length 30m and diameter 53mm (50 mm NB) to investigate the slurry flow behaviour through the pipe bend. The concentration of solid particulates by weight was varied in the range of 50 to 65% and particle median diameter ( $d_{50}$ ) chosen to be 24  $\mu\text{m}$  in order to predict the relative pressure drop, loss coefficient and permanent pressure drop for the bend. They observed that the relative pressure drop increases with the increasing velocity and tending to a constant value corresponding to high velocity for all the concentrations. The bend loss coefficient was found to reducing with the increase in flow velocity for all the concentrations.

**Mosa et al. (2007)** experimentally studied the effect of pH, temperature and particle size on rheological nature and pressure drop characteristics of coal water slurry. They have used a pilot plant test loop with the diameter of pipeline as 63mm (NB) and length as 41m for studying the effect of particle degradation on pressure drop characteristics. The particle size of coal was taken as 250  $\mu\text{m}$  during the preparation of slurry. The coal water concentration was maintained at 10% by weight, room temperature and pH to be 7 during the experimental run. They studied the rheological behaviour of solid liquid slurry by varying the pH value from 1 to 12 and found that the pseudoplastic behaviour of coal slurry decreases with the increase of temperature as well as pH upto 6. They observed that the pressure loss increases with the increasing degradation of particle.

**EL-Nahhas et al. (2009)** experimentally studied the effect of different particle size of quartz sand on flow characteristics of slurry. They employed a pipe loop made of stainless steel having dimensions of pipe length and diameter to be as 18m and 26.8mm respectively. The sand particles of three different sizes ( $d_{50}$ ) such as 0.2, 0.7 and 1.4mm were taken to prepare the slurry of different solid sizes and the concentration was varied in the range of 4 to 33%. The frictional losses were found to vary in direct proportion with concentration for fine and coarse sand slurry but they had a little effect of velocity varying above than 5m/sec in case of medium sand slurry.

**Chandel et al. (2009)** experimentally studied the pressure drop characteristics for the flow of fly ash slurry considered at various concentrations with and without additive. Along with this, the effect of additives mixture at 5:1 of sodium carbonate and Henko detergent on pressure drop was

investigated. They employed a pilot plant test loop having dimensions of pipeline for length and diameter to be 50mm and 42mm respectively. The  $d_{50}$  and weighted mean sizes of the particle for fly ash were noted to be 40 $\mu$ m and 25 $\mu$ m respectively. The solid concentration by weight was varied from 60 to 70%. For the measurement of flow rate, a pre-calibrated electromagnetic flow meter (ABB Limited) was installed in the vertical pipe section of the loop. The results obtained experimentally and obtained analytically were compared based upon Darby and Melon Model and the results were found to be in good agreement with each other. The result shows that the pressure drop increases with the increase of concentration and velocity but on addition of additives, the pressure drop tends to be decreasing.

**Liu et al. (2009)** experimentally studied the pressure drop characteristics for the flow of solid liquid mixture passing through different geometries of pipe fittings. They employed different pipe fittings, namely bends of diameter 25 mm, 40mm and 50mm with  $R_c/D$  varying from 1.5 to 6, Gradual contractions where contraction angles varying from 3° to 90° and sudden contraction with diameter ratios of 50mm/25mm and 68mm/25mm. They had taken coal powder from two places as a solid material. Out of these two coal samples, the concentration of one sample by weight varied from 57 to 59% and another from 59 % to 62 %. They observed that the CWS exhibits three regions, namely shear thinning at low shear rate, Newtonian and shear thickening behaviour for the concentration less than 60 %, while for the concentration exceeding 60 %, it shows shear thinning and Newtonian behaviour with increasing shear rate. They found that the pressure loss in case of gradual contraction first reduces to a minimum and then increases with the increase in angle. In case of sudden contractions, the pressure loss was found to increase with the increasing diameter ratio.

**Chandel et al. (2010)** studied experimentally the pressure drop characteristics for fly ash and bottom ash slurry flowing through a pipe loop at high concentration (50-70% by weight). They employed a closed loop of mild steel pipe having dimensions of pipe length and diameter to be as 50 m and 42mm respectively. The fly and bottom ash was mixed in 1:4 ratio by weight. It was observed that the pressure drop at certain velocity increases with increasing the solid concentration. From the view point of specific energy consumption, it was seen that the SEC decreases upto the 65% concentration of solid by weight and beyond this concentration, it

increases further. At a given concentration, relative pressure drop was observed to decrease with the increasing flow velocity.

**Chen et al. (2010)** experimentally investigated the effects of concentration by volume, slurry temperature and particle size on wall slip characteristics (wall slip velocity, critical wall shear stress and slippage contribution) of coal water slurries (CWSs) in steel pipes having the diameters of (25, 32, 40 and 50 mm) and length of 2200mm. To study the effect of particle size, they employed two particles of  $d_{50}$  sizes (24.1 and 442.9  $\mu\text{m}$  at solids concentration of coal water slurry 51.7% by volume. A screw pump flow rate of 16  $\text{m}^3/\text{h}$  driven by an electromagnetic adjustable speed motor was used to pump the slurry. It was concluded that the wall slip velocity decreases with increase in concentration and increases with increase in temperature or particle size.

**Seitshiro et al. (2013)** experimentally studied the hydraulic gradient characteristics for mixed-sized slurry flowing through a horizontal pipeline and compared the result with the theory by employing two models, namely, condolios-chapus and Wasp method. They employed transparent Perspex pipe having dimensions of pipe length and diameter to be as 25.7 m and 2.62 cm respectively. The solids, namely, coloured bakelite and sand, were taken during the preparation of mixed-sized slurry. The particle diameter of sand and bakelite were to be taken in the range of 1.21 mm to 2.18 mm and maximum concentration to be 25%. The Wasp method was seen to be applied for the mixed-sized slurry flows during low concentration range. They found that hydraulic gradient decreases with increasing the mixture ratio.

**Kaushal et al. (2013)** numerically simulated the slurry flow by employing Eulerian two-phase which is one of the multiphase models used in fluent software. A three dimensional non-uniform grid of hexagonal and cooper type shape was chosen to discretize the whole domain of computation The modeling results were made to compare with the experimentally collected data in 53.0 mm diameter horizontal bend having radius of 148.4 mm for pressure drops. The Simulation was performed with various concentrations of silica sand ranging from 0% to 16.28% by volume having the median particle size of 450 $\mu\text{m}$  and for each concentration; the flow velocity was varied from 1.78 to 3.56 m/s. They concluded that the prediction pressure drop for

slurry flow through horizontal 90<sup>0</sup> bends can be done in CFD- fluent software with such a fair accuracy. However, the results deviated from the measured values as the concentration found increasing. It was also observed that bend loss coefficient ( $k_t$ ) reduces as the flow velocity increases and also as efflux concentration decreases.

**Shah et al. (2013)** studied the solid velocity and concentration fluctuations for concentrated sand water mixtures (20-35% by volume) flowing through horizontal pipeline. Experiments were conducted with very fine particles of sand flowing through the horizontal pipe loop having an internal diameter of pipe 52mm at mixture velocities ranging from 2 to 5m/s. They found that the magnitude of local solid concentration is greater near the pipe wall and increases with the increase in mixture velocity. Solid axial turbulent intensities were found to be higher near the pipe wall because of particle wall interactions.

**Senapati et al. (2013)** investigated experimentally the flow of coarse bottom ash conveyed with the finer fly ash slurry flowing through pipeline in the concentration range of 62.5 to 67.5% by weight. They have used a pilot plant test loop with the diameter of pipeline as 50mm and slurry velocity ranging from 0.9 to 2.8 m/sec. The fly ash, bottom ash was mixed in the ratio of 5: 1 present at 9-52  $\mu\text{m}$  as median particle range. The mixture was found to be pseudoplastic in the concentration range of 62.5 to 67.5%. It was observed that the head loss taken for two fly ash samples increases with an increase in solid concentration under the range of flow velocity. One of them samples of fly ash incurred lesser head loss after the addition of solid concentration of coarse bottom ash because of increasing median particle size and reducing specific surface area of the sample hence the addition of coarse bottom ash in fly ash induced some drag reducing effects resulting in reduction in head loss.

**Ravelet et al. (2013)** experimentally studied the pressure drops characteristics for solid liquid mixture flowing through the pipe loop. They employed pipeline having dimensions of length and diameter to be 30m and 100mm respectively. They had taken four samples separately for testing. Out of them, three samples were of alumina and one of stones. The  $d_{50}$  size of three mixtures of alumina was noted to be 10.5mm, 8.25mm and 5.5mm respectively whereas the last sample of stones ranging from 8mm to 18mm and  $D_{50}$  of 10mm was used for the study. Particle sizes were varying in the range of 5% to 18% of the pipe diameter. Two specific masses of 3.65 and 2.5 for

the solids in the shape of spheres were taken for the experimental study. It was seen that the pressure drops are lower for large particles in horizontal pipe than those measured in vertical pipe. The pressure drops in case of mixture observed to be significantly higher than those measured for a pure fluid for the whole range of mixture velocity. During the experiment they observed that the critical velocity seems to be unaffected with the particle sizes. Increasing the specific mass led to an increase in both pressure drop and critical flow velocity.

**Abd Al Aziz et al. (2013)** studied the parameters affecting the pipe flow characteristics during the slurry flow through pipeline. They tested the sand slurry and mud slurry flowing through the 285 meter long pipeline. The parameters were found by using a non-dimensional approach which included Reynolds number, Froude number, Concentration, Specific gravity and ratio of particle to pipe diameter. By varying the Reynolds number from 10907 to 63699 and Froude number (0.5-17) with the flow velocity they found the pressure gradient and efficiency of transport to be increasing with these numbers. This concept posed an idea of increasing the flow velocity in order to avoid blocking slurry pipelines. They observed that the pressure drop increases and efficiency of transport decreases with the increase in particle diameter. It was also seen that high values of Reynolds number increase the ability to transport large grain sizes.

**Malavasi et al. (2013)** numerically studied the flow of a solid-water mixture through an upward-facing step in a channel. They studied the effects of expansion ratio of 0.50 and 0.67, particle diameter of 125 $\mu\text{m}$  and 440 $\mu\text{m}$  and mean solid volume fraction between 0.05 and 0.20 on the velocity and pressure distribution. Particle density was taken to be 2465 kg m<sup>-3</sup>. An Eulerian two phase model was used to simulate the flow and it was validated by comparison to other numerical investigations and to experimental data about the horizontal pipe. They also studied the effect of the above parameters upon the degree of coupling between the phases and the extension of the disturbance region in the pressure and solid volume fraction fields downstream the step.

**Kim et al. (2013)** investigated numerically the flow of mixture of sand and water flowing through circular pipeline by employing the Eulerian granular multiphase (EGM) model and K- $\epsilon$  turbulence model in the commercially available FLUENT software. The specific gravity and

median particle size ( $d_{50}$ ) of the sand were taken to be 2.65 and 0.54mm respectively. The non-uniform system of grid having hexahedral elements was chosen for discretising the pipeline domain. The computational results were compared with the experimental results calculated for the pipeline and particle diameter to be 51.5mm and 0.165 mm with the delivered concentration by volume to be 8.4 % .They computationally studied the effect of Reynolds number and delivered concentration by volume on hydraulic gradient. The hydraulic gradient found to be decreasing with the increasing volumetric concentration for the smaller values of Reynolds number.

**Eltoukhy (2013)** investigated experimentally the flow of sand-water mixture through inclined pipes in such a manner that the inclination of pipe varies in the range of 0 to 90 deg. for both the directions of flow as upward and downward. During the experimental run various parameters related to sand like median grain size ( $d_{50}$ ), relative density and solids concentration by volume were noted to be 0.20mm, 2.67 and 15% respectively. The effect of solid concentration, velocity of flow and geometry of the pipeline upon head losses was observed. The differential manometer was actually used to measure the head losses across horizontal and inclined pipes. By doing the experiment, it was concluded that the hydraulic gradient goes on increasing with the increasing concentration by volume, velocity of flow and inclination angle from 10 to 45 degree.

**Nabil et al. (2013)** studied experimentally the flow of solid-liquid particulates mixture through pipeline network having a pipe loop comprises up the pipeline made of stainless steel with an internal diameter of 26.8 mm. There were three samples of quartz sand namely fine ( $d_{50}=0.2$ mm), medium to have the particle median dia.of 0.7mm and coarse ( $d_{50} =1.4$ mm) used for the study purposes. The concentration by volume of solid particles was changed from 5% to 30% during the flow analysis. The effect of slurry velocity, particle size and solid concentration was seen upon the drop in pressure of settling slurries flowing through pipeline. It was noticed that with an increase in the velocity of slurry flow, the pressure drop finds to increase. The pressure drop was also found to be increasing with increasing concentration but taken at same velocity. Pressure found to be increased with a smaller rate at concentration for the small values of velocity but found to be increasing with a rapid rate at different concentrations for large values of velocity. The results obtained from the experiment were compared with the simulations done

with the help of Fluent software 6.3 using Eulerian-Eulerian Approach and standard K- $\epsilon$  turbulence model.

**Pinto et al. (2014)** studied experimentally the critical velocity for the flow of different mineral slurries through pipeline. They employed two pipe loops having the dimensions of internal diameter of pipeline noted to be 25 mm and 50 mm respectively. The coarser particles of quartz, apatite and industrial concentrate of hematite were divided into two classes of particles (class 1 from 0.210 mm to 0.297 mm and class 2 from 0.105 to 0.149 mm) in order to prepare the slurry of each mineral separately. Each slurry concentration (8% to 27%) by volume was varied and flow velocity varied in the range of 0.8 to 3.6 m/ sec. The pressure drop for each mineral slurry at various concentrations was found to minimum within the flow velocity ranging from 1.2 to 2 m/sec. They observed the critical velocity for which the slurry pressure drop reaches to minimum with the increasing bulk flow velocity.

**Massoudi et al. (2014)** studied experimentally the pressure drop characteristics of biomass suspensions flowing through pipeline. They employed five different substances, namely, crushed leaves, coffee powder, salt, sand and mulch, forming biomass suspensions taken at low concentration of 2%, 4% and 6% for mulch, dried leaves and coffee powder, for sand (2%, 4%) and for salt water (10%, 20%, 25% and 30%) Whereas the size in mm of mulch, coffee powder, dried leaves (1.51, 3.3, 2.94) and for sand (0.03-2). It was found that the pressure drop in case of coffee powder, mulch and crushed leaves, increases non-linearly with the flow rate that never observes in case of homogenous system.

**Rao et al. (2014)** investigated numerically the pressure drop characteristics for the flow of bottom ash and fly ash mixtures through straight pipe. The straight pipeline and 90° bend were modeled in Gambit version 2.2. The bottom ash to fly ash was maintained at different values, namely 6:4, 8:2 and bottom ash mixed with 4%, 6% additive. The bulk flow of slurry was varied from 1.5 to 3m/sec at different solids concentration (20%, 30%, 40% and 50%). It was found from simulation that the pressure drop goes on increasing with increasing flow velocity and concentration by weight of combination of fly and bottom ashes. At low concentration of solids pressure drop was found to be less for bottom ash mixed with additives in comparison to bottom ash mixed fly ash at different mixture ratios.

**Csaba et al. (2014)** investigated the loss coefficients during the flow of Bingham and power law fluids through pipe components like elbows and diffusers. They carried out three fluids namely water, power law fluid and Bingham Plastic fluid flowing through diffusers and elbows for the results of simulation. After comparing the results with experimental data they concluded that the CFD results are underestimated. During the Bingham fluid flow through elbows and diffusers, there was an existence of critical Hedstrom number, below this number the loss coefficient was 13 found to be independent of the Reynolds number. Finally, they suggested the use of SST rather than  $K - \epsilon$  model in evaluating the flow field rightly.

**Hashemi et al. (2014)** investigated the specific energy consumption (SEC) for settling slurry constituting up the coarse particles of size ranging from  $150\mu\text{m}$  to  $2000\mu\text{m}$  in varying solid concentration by volume at mixture velocities up to  $10\text{m/s}$  and pipe diameters  $0.15$  and  $0.4\text{m}$ . The near wall lift model affecting the specific energy consumption was employed during the flow of settling Slurry through pipe model. It was found that with increase in mixture velocity at constant solid concentration, the SEC value drops to decrease and reaches to its minimum at specific velocity as the lowest value for SEC corresponding to maximum transport efficiency was found at solid concentration around 30% therefore, the results revealing that SEC increases with increase in particle diameter.

**Luk et al. (2014)]** experimentally studied the effect of particle size and saturated solid mass fraction of wheat straw slurry on pressure drop gradients. They employed a laboratory scale pipe loop of length  $12.8$  mm and diameter  $50\text{mm}$  to investigate the flow behavior of slurry through pipeline. The fraction of water by mass in saturated material of biomass varied in the range of 77.5 % for short particles and 79.0 % for long. They observed that the pressure drop reduces with the short particle sizes rather than long. The lowest pressure losses were observed with particle size of  $3$  mm long and saturated solid mass fraction ranging from 20 to 30 % by weight being pumped at velocity of  $1.5\text{m/sec}$ . However, pressure losses were observed close to water at low velocities ranging from  $1.5$  to  $2\text{m/sec}$  and low saturated solid mass fraction of 10 to 20 percent. On the other hand, slurries flowing with 20 to 30 % with saturated solid mass fraction and velocity of  $1.5$  m/sec observed to take a lowest pumping requirement.

**Vaezi et al. (2014)** studied experimentally the pressure drop characteristics for the flow of agriculture residue through pipeline. They employed a pipe loop having dimension of pipeline length and diameter noted to be 25m and 50mm respectively. The agriculture residue of Corn stover and wheat straw having particles of sizes such as less than 3.2mm, 3.2 mm at concentration 5 to 40 % for less than 3.2 mm and 5 to 35% for 3.2 mm were taken for preparing the slurry separately. The flow velocity was varied in the range of 0.5 to 5m/sec. The pressure drop observed experimentally and predicted analytically and the prediction of pressure drop was found to be in good agreement varying with the pipe diameter as the power of diameter to be - 1.2.

**Vlasak et al. (2014)** studied experimentally the effect of velocity of mixture and solid concentration on pressure drop characteristics for the flow of coarse particles slurry through horizontal and vertical pipelines. They employed stainless pipeline having dimensions of pipeline in terms of its internal diameter as 100mm. The coarser particles of size ( $d_{50}$ ) as 11mm and density 2787 being  $2787 \text{ Kg/m}^3$  where concentration by volume ranging from 3 to 15% were taken to study the effect of particles. The bulk flow velocity ranging from 1.5 to 5.5 m/sec was taken during the study. They found that the pressure drop in case of vertical pipe is less than as compared to the horizontal pipeline because of the contact in horizontal pipe produces a large amount of friction loss than in vertical pipe.

**Malavasi et al. (2015)** numerically improved the model by considering the following concerns like wall boundary condition in case of solid phase, an empirical correlation for studying the viscosity of the mixture accounting the particle shape by means of law linking the viscosity of the mixture to the solid volume fraction and a new solution algorithm reducing the computation time. They also varied the flow conditions such as pipe diameter, particle size and mean delivered solid concentration by volume, as well. The main improvement was noticed in the accuracy of pressure gradient prediction as the deviations being lower than 5 % indicated by the parity plot. They discussed the model applicability with the sand slurry having fully- suspended flows where the dispersed phase consists up of spherical glass beads.

## 2.2 RHEOLOGICAL BEHAVIOUR OF SOLID LIQUID MIXTURE

In order to determine the characteristics of slurry like pressure drop measured at different locations inside slurry pipeline, it becomes very much important to evaluate the parameters relating to rheology of slurry thus determining the pressure drop characteristics in a right manner even with limited scale pilot plant test loop. Concerning slurry pipeline design for the hydraulic disposal of solid liquid mixture at high concentration, the first or primary thing which needs to be done, is to go through the rheological behaviour of slurry.

**Nguyen et al. (2007)** studied the rheological behaviour of coal water slurry. Two coal samples of low in rank from South Australia were taken up. The concentration of fine coal particles was studied in the range of 23% to 50% Fine particles of size less than 45  $\mu\text{m}$  were used to make up the coal slurry. The bimodal slurry was prepared by adding coarse particles of size ranging from 208 to 279  $\mu\text{m}$ . At lower concentration, the slurry observed to exhibit a Newtonian behaviour. However, the slurry observed to have viscoplastic behaviour with a certain value of yield stress at high concentration above than 40%. The viscosity of coal slurry consisting of fine particles was found to decrease with the addition of coarse particles to fine particles.

**Mishra et al. (2010)** studied the rheological behaviour of coal water slurry having high concentration noted to be at 50%, 55% and 57% respectively. The effect of amount of ash in coal, concentration of solid on the rheological nature of CWS was studied. The sample of coal was taken from Talcher coal field, in Orissa. A Haake viscometer was used for studying the rheological behaviour of coal water mixture. It was seen that the CWS exhibits pseudoplastic behaviour at high concentration. As the amount of ash increased, the apparent viscosity of CWS was found to increase with the amount of ash. The apparent viscosity was observed to be high with the low pH value.

**Zhou et al. (2010)** studied the rheological behaviour of concentrated coal water suspension. Here, the Datong coal was used for the preparation of concentrated CWS. Two types of coal water slurry were prepared by mixing the lignin based dispersant at a dosage amount of 0.7% and 1.5% by weight with the coal concentration to be 64% by weight. The viscosity was measured with the help of Haake rheometer. They concluded that for first slurry, when the dosage of dispersant noted to be 0.7%, the slurry exhibits pseudoplastic behaviour. While, on the

other hand, during the dispersant to be 1.5%, the slurry exhibited characteristic of shear thickening. Among all the five models, the Herschel- Bulkley model was found to be best fitted curve for studying the rheological property of coal water suspension. The factors responsible for rheological study of CWS such as coal concentration by weight, and dosage of dispersant affects the rheological property to an extent. They found that the CWS slurry exhibits pseudoplastic behaviour with increasing concentration of solid and with increasing value of dispersant dosage, the CWS shows dilatant flow characteristic.

**Ugwu et al. (2013)** studied the rheological behaviour of coal water mixture fluid along with the effect of solid concentration by volume at 30%, 40%, 50% and 55% on characteristics of flow and rate of settlement of coal water mixture fluid. The coal sample used here was subbituminous coal taken from Kogi State in Nigeria. The rotational viscometer was used for studying the rheological nature of coal water slurry. Anionic liquid soap was used as a surfactant while preparing the slurry. From the view point of plot analysed between viscosity and shear rate, the behaviour of the slurry above 30% was known to be non-newtonian. The pseudoplastic behaviour of slurry was found to be at or above than 40% concentration. At 30 % concentration, it was seen that the slurry settles faster than with any other concentration.

**Li et al. (2014)** studied mainly the effects of gradation in coal powder, pre-adsorption of water, addition of modified sodium lignosulfonate (SL-M) as a dispersant and preparation of slurry by mixing two coal samples taken from two places on the superficial viscosity of the CWS. Coal water slurry was prepared by employing two coals, namely Shenhua coal of low rank and Shandong coal of medium rank. The apparent viscosity of slurry was measured using Haake, RotoVisco 1 viscometer. They found that as the solid content inside slurry increases, the apparent viscosity increases for both coal slurries such as low rank and medium rank as well. The slurry performance was observed to be improving with the mixing of two rank coals, in terms of reducing the apparent viscosity for combined slurry. On pre-adsorption of water in coal slurry of low rank, the apparent viscosity was found to remain same as earlier even after the solid concentration increasing upto 3 %.

**Panda et al. (2014)** studied the rheological nature of fly ash and fly ash-bottom ash mixtures at high concentration (60 % and above upto 65%). Addition of bottom ash in fly ash was carried on at 10 %, 20%, 30% and 40%. The samples of fly ash and bottom ash were collected from

Thermal power plant of Talcher. The particle median size ( $d_{50}$ ) of fly ash and bottom ash samples were noted to be 20  $\mu\text{m}$  and 250  $\mu\text{m}$  respectively. The rheology of samples was studied using Haake Rotational Viscometer. From the rheological study, it was found that the slurry of fly ash sample at 60% and above than 60% shows up the nature of Bingham plastic fluid but after adding on bottom ash, the slurry shows yield pseudoplastic fluid. They also studied the procedure of calculating the friction factor for both types of fluid such as Bingham as well as pseudoplastic fluid.

**Panda et al. (2014)** studied the rheological properties of coal slurry consisting of coal having content of ash to be high and calorific value to be low. Also, the empirical relationship was derived between apparent viscosity and solid volume fraction of coal having high ash content. The rheology of the sample was studied using Haake rotational viscometer. From the rheological study of coal water slurry, it was concluded that the apparent viscosity increases exponentially beyond the concentration of solid above than 50%.

**Senapati et al. (2014)** studied the rheological behaviour of fly ash and the combination of bottom ash and fly ash samples in the range of concentration from 60 to 67.5%. Bottom ash to fly ash was added up in the varying range 0 to 20% of the amount of solids present at given concentration. The ash samples were collected from NTPC Plant in Talcher, Odisha. The particle median size ( $d_{50}$ ) of samples, namely fly and bottom ash was noted to be 16.4 $\mu\text{m}$  and 144 $\mu\text{m}$  respectively. The rheology of samples was studied using Haake Rotational Viscometer. From the rheological study, it was found that the slurry of different ash samples in the concentration range of 60 to 67.5% by mass, exhibits pseudoplastic behaviour. After this, the frictional head loss for the nominal bores (100 to 300mm) was evaluated by employing the power law model of non-newtonian subdivision. At a given concentration of solids, adding up the bottom ash to fly ash slurry results in lower pressure drop thereby decreasing requirement of pumping.

**Singh et al. (2015)** studied mainly the effect of size of particles, temperature of slurry and concentration of solid by weight at 30%, 40%, 50% and 60% on rheological behaviour of slurry prepared from coal and water. The sample of coal was taken from the mining site of Assam. The rheological study was carried on for both kinds of particle size distribution such as unimodal and bimodal distribution of particles. The rheology of sample was studied using Anton Paar rheometer. From the rheological study it was concluded that as concentration of solid increases,

the apparent viscosity also increases with it. The pseudoplastic behaviour of slurry was observed at high concentrations. However, in the case of bimodal slurry, the apparent viscosity of slurry made of fine particles being mixed with coarse particles was also found to decreasing upto certain fraction of coarse particles. On further addition of coarse particles in fine particles slurry, the apparent viscosity increases. The effect of temperature was studied in such a manner that with increase in temperature, the apparent viscosity decreases.

**Pani et al. (2015)** studied the rheological behaviour of fly ash sample in the range of concentration of solid from 50 to 60% by weight. The sample of fly ash was collected from captive power plant at JSPL in Rajgarh, Rajasthan where the particle median size ( $d_{50}$ ) was noted to be 34  $\mu\text{m}$ . The rheology of the sample was studied using Haake Rotational viscometer. Additives like Sodium silicate and Ghadi detergent were added up. From the rheological data, it was observed that the slurry, in the concentration ranging from 50 to 60% by weight, in the absence of additive, exhibits Bingham plastic behaviour and flow pattern seems to be non-newtonian. On the other hand, with increase in solid content, the viscosity was observed to be increasing. However, the effect of additives was seen in such a way that on addition of additives in percentage from 0.2% to 0.6% into fly ash slurry, the apparent viscosity goes on reducing. But the effect of additive was seen more in case of sodium silicate rather than Ghadi detergent.

### **2.3 CHARECTERISATION STUDY OF COAL AND ASH SAMPLES**

**Ma et al. (2015)** studied properties like microstructure, chemical composition and size distribution of particles of coal and fly ash samples by employing the technology of scanning electron microscopy, coulter particle analyzer and energy dispersive spectrometer. They studied mainly the influence of coal in pulverized form on the fly ash characteristics using these techniques as mentioned earlier. They employed four coal samples as well as four fly ash samples from four different places. As per the chemical composition of coal, all the four samples of coal containing non-metallic elements take account of carbon, silicon and oxygen while metallic elements include aluminium, magnesium and calcium. However, the fly ash samples containing non-metallic elements as in coal with sodium and iron in addition to metallic elements as in coal are found. It was seen that most of the particles in coal are irregular in shape and in fly ash they were spherical. The median size of coal particles were found to be ranging from 20 to

32 $\mu$ m and fly ash particles as ranging from 3 to 5 $\mu$ m. They concluded that the fly ash particles don't affect too much even after the uneven distribution of particles of coal.

## **CHAPTER 3**

### **CHARACTERIZATION OF COAL**

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The various physical properties of coal generally affect the characteristics of flow of slurry in a pipe line. So it is necessary to gain the knowledge of coal sample being used for the present study. The various tests like Scanning Electron Microscopy (SEM)-Energy Dispersive X-Ray Spectroscopy (EDS), X-Ray Diffract gram (XRD) pattern, Particle size Distribution (PSD) are conducted to study the physical properties of coal. The above mentioned characterization techniques are used to familiarise with the properties that may affect the hydraulic transport of material through pipe network. For example, particle size affects the hydraulic gradient characteristics of the flow of solid liquid mixture through pipe. Too small size of particles is the reason of forming the cake that results in higher pressure drop (Ma et al., 2015). In present study coal sample 1 and 2 were taken from the mining of Jharkhand and from the mining of Assam respectively. The flow characterisation studies of above mentioned coals were done and the results thus obtained were analysed both graphically and analytically.

#### **3.1 PARTICLE SIZE DISTRIBUTION (PSD)**

Particle size distribution is defined as the particles are separated out in sieves with respect to their sizes. The particle size of coal affects the rheological behaviour of coal water slurry. It affects many other properties of coal like bulk density and permeability. There are many ways by which the sieve can be represented as aperture size, mesh size or sieve number. It may be wet or dry sieving. It can be done either by using machine or by hand. The shaking of sieve is done for a constant period of time unless the powder retains on the sieves. The advantage of this technique is that it can be performed easily and it is an inexpensive process. The sieve analysis is performed by taking the weight of coal sample approximately 100 grams and is kept inside the oven at temp of around 120° C for about 1 hour and 15 minutes in order to remove the moisture from the sample. After making it dried, the sample is kept over the sieve of size 500 microns. Then the sample was sieved through a set of British Standard Sieves ranging from 500 microns

to below than 53 microns. For this experiment 500, 355, 250, 150, 106, 75 and 53 microns sieves are used. The weight of coal sample collected on the top of each sieve was retained and measured by means of weighing machine. The same procedure is repeated twice. To get the percentage retained on each sieve, the mass retained on each sieve is divided by the total weight of the sample. Table 3.1 shows the classification of particle size into various categories in accordance with the sizing of particles.

Table 3.2, Figure 3.1 shows the particle size distribution analysis of coal samples. It concludes that all the particles are found to be finer than 500 microns in both the coal samples. Around 14.35% and 17.85% particles are found to lie in the range of 150 to 250 $\mu$ m in coal samples 1 and 2 respectively whereas 42.66 and 28.11% are lying below 75  $\mu$ m.

### **3.2 SCANNING ELECTRON MICROSCOPY (SEM)**

The Scanning Electronic Microscopic images find their usefulness in studying the topography and morphology, Chemistry related things like phases and elemental composition, Crystallography and orientation of grains. In this technique a 2 dimensional image is produced by means of taking up a spectrum considered over a region of the sample. Backscatter electrons generate from the complete volume considered for the beam and they are high energy electrons. By placing the secondary electro detector in the lens, the resolution of the images can be improved which may be basically lying upto 1 to 2 nm. The SEM images application can be seen upon many areas like fracture surfaces, electronic devices, fibres, coatings and particles, as well. The coal sample 1 and 2 were analysed using SEM technique using the application of 6510 LV model SEM Machine (JEOL made) placed at SAI Lab working in the range of 10 to 20 KV.

On the basis of shape and structure of particles, the classification of particles can be done using SEM analysis i.e. spherical, plerospheres and irregular particles (Ma et al., 2015). Figure 3.2, 3.3 shows the SEM analysis of coal samples at 100 resolutions and concludes that the coal particles in both the coal samples are found to be irregular in shape.

### **3.3 ENERGY DISPERSIVE X-RAY (EDX)**

Energy Dispersive X-ray spectroscopy technique known by different names such as Energy Dispersive Spectroscopy (EDS), EDAX, EDXRF, is basically an analytical technique. The basic principle upon which it depends, is the interaction between electromagnetic radiation and matter where the charged particles present inside the matter emit the x-rays. Each element possesses a different atomic structure and releases a unique set of peaks over the spectrum. This technique is useful in identifying the particular elements along with their relative proportion present inside the sample. It involves the scanning of the particular region of the SEM images for the generation of spectrum of x-ray. INCA X-act model of EDX machine is used for the EDX Analysis. “Noran System Six” the name of software, is mainly installed in the machine of EDS to comprehend with the energy level of the x-rays. Here, the samples of coal sample (2) was analysed in order to find out their composition both element wise as well as compound wise.

Table 3.3 shows the elements and compounds tested in coal sample. The sample of coal contains the major proportion of carbon dioxide about 99.03%. In addition to  $\text{CO}_2$ ,  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  are also found in minor proportion as trace compounds.

### **3.4 XRD (X-RAY DIFFRACTION)**

In the case of X-Ray diffraction technique a measurement is being noted in such a way that a piece containing sample amount with gold coating is placed on the Goniometer which rotates gradually during the bombardment of X-rays on piece. In every case of bombardment a regular spot of diffraction pattern is produced.

A sample with respect to its purity and impurity in terms of its chemical constituent presence can be determined with the help of diffraction pattern. It is a non-destructive kind of technique characterizing the crystalline material. This is useful in determining the structural properties like strain, Average Grain size, texture, phase composition and atomic arrangement, as well. The diffraction patterns are produced as monochromatic light of x-rays making up the constructive interference gets scattered at specific angle after passing through lattice planes present in a sample. These diffraction patterns obtained after the scattering of x-rays by crystal are totally dependent upon Bragg's law. Here, at SAI Lab the PANALYTICAL ('X' pert pro)

diffractometer model is used to study the mineralogical composition of coal sample (2). Cu was taken as an anode material and the scan performed at the angle of 2 theta ranging from 10 to 90<sup>0</sup>.

Figure 3.4 shows the X-ray diffraction of coal sample. It concludes that dominantly three compounds namely kaolinite, quartz and Iron sulphate is observed in the coal sample (2) and they are also seen at highest peaks in the coal sample (2).

### 3.5 PROPERTIES OF COAL

- **Specific Gravity:** Specific gravity or Relative density of a substance is basically the ratio of density of the substance to the density of the reference material like water in case of liquids and air in case of gases. Specific gravity depends upon the porosity of the substance. For the same type of coal, higher ash coals have higher specific gravity. The true specific gravity measurement in case of bituminous coals generally varies from 1.27 to 1.45. Thus mathematically it can be written as:

$$SG_{\text{apparent}} = \frac{W_{\text{A sample}}}{W_{\text{A H}_2\text{O}}} \text{ or } SG_{\text{true}} = \frac{\rho_{\text{sample}}}{\rho_{\text{H}_2\text{O}}} \quad (3.1)$$

- **Plasticity:** The main reason of plasticity in coal slurry depends upon microstructure of coal, water content and percentage of chemical constituents. The coal powder generally finds to be non-plastic.
- **Bulk Density:** The Bulk density gives an idea about the weight of material for a given volume. It is not a fundamental property of any material as it depends upon the handling of material, amount of water present in the material and mineralogical composition of the material. The total volume occupied by the material comprises of volume of the particles, voids present in the particle and pore volume. The bulk density of coal decreases with the increase of moisture content. It varies from 400 to 500Kg/m<sup>3</sup> for pulverised coal.
- **Water Holding Capacity:** The water holding capacity of any material depends upon its texture as well as organic matter present in material as the capacity to hold water in substantial increases with increasing the organic matter. More the proportion of particles of mud and sediment present in a material, more will be the percentage of water holding

capacity. Particle size greatly affects the water absorption capacity of sample. More the finer particles present in sample, lesser will be the water holding capacity (Lyer et al., 1999)

- **Porosity:** The void fraction or porosity is basically the ratio of voids volume present in the material to the total volume of the material. It usually lies in the range of 0 to 1. In case of solid-liquid flowing through channel, this term is defined in such a way that the ratio of volume that has been occupied by solid particulates to the total volume of channel. As the particle size increases, the porosity decreases with it. Thus mathematically can be written as:

$$\emptyset = 1 - \frac{\rho_{\text{bulk}}}{\rho_{\text{particle}}} \quad (3.2)$$

### 3.6 PROXIMATE ANALYSIS OF COAL

The proximate analysis of coal specifies that the coal contains the amount of moisture, fixed carbon, ash content and volatile matter. The amount is usually taken in percentage by weight.

- **Moisture** The wet coal on exposure to atmosphere removes its external moisture by evaporation but on the other hand, removal of moisture from apparently dry coal takes place by heating above than 100°C.
- **Fixed Carbon** It is generally the non-volatile deposit of the pure coal. The amount of fixed carbon is calculated as the sum of percentage by weight of moisture, ash and volatile matter getting subtracted from 100. The fixed carbon includes the carbon itself with some trace elements like nitrogen, hydrogen, oxygen and sulphur.
- **Volatile Matter** It does not take into account the moisture present in coal but it considers the formation of water from the combination of hydrogen and oxygen which form during decomposition. As the percentage of volatile matter increases, the amount of fixed carbon in terms of percentage by weight decreases.

- **Ash Content** The coal containing inorganic mineral matters gets converted into ash by chemical reactions during combustion of coal. The coal ash consists of silica, oxides of iron, lime and alumina.

The below mentioned Table 3.4 shows the proximate analysis of coal samples. This experiment was conducted at Chemical Engineering Lab in Thapar University by applying the test procedure of IS code 1350. The analysis was performed upon air dried basis.

### **3.7 ULTIMATE ANALYSIS OF COAL**

The elemental composition of any fuel like coal can be found by doing ultimate analysis of that fuel. The elements such as nitrogen, sulphur, hydrogen, carbon and oxygen constituting up the clean fuel are measured in percentage by weight. The sample weight of 2 mg was taken while performing the test. This analysis plays an important role in determining the amount of air required for complete burning of fuel. The below mentioned Table 3.5 shows ultimate analysis of coal sample (2).

### **3.8 HYDROGEN POTENTIAL (pH) ANALYSIS OF COAL**

It is defined as power of hydrogen ion concentration, written mathematically as  $-\text{Log}_{10} [\text{H}^+]$ . A value of pH less than 7 indicates acidic character whereas greater than 7 indicates basic character. More the concentration of  $\text{H}^+$  indicates more acidic character and more concentration of  $\text{OH}^-$  ion indicates more basic or alkaline character of substance. The coal filling effect on coal water slurry can be determined to great extent by measuring its pH. pH of coal water slurry of two different coals samples at different solids concentration by weight are measured using digital pH meter. Figure 3.5, Table 3.6 shows that the pH value of both coal water slurries decreases with the increasing concentration of solids by weight. pH affects the rheological behaviour of coal. The pseudoplastic nature of coal slurry sharply decreases with increasing pH upto 6 (Mosa et al. 2007).

### **3.9 THERMAL ANALYSIS OF COAL**

This technique is mainly dealt with the change in mass of the matter measured against the time or temperature where heating or cooling done at a predetermined rate. This analysis is more or

less depends upon the condition of atmosphere whether the atmosphere is oxidative or inert. The nature and shape of thermal curves also depends on the shape of sample holder. The amount as well as the size of the particle also affects the thermal curves. With the help of thermal gravimetric analysis, the temperature upto which the material does not loose the weight and at what temperature the material starts to decompose can be determined.

Due to heating and cooling of material, the crystal structure of material will change by decomposition, expansion, contraction, fusion and phase transition. All the above mentioned changes could be easily judged by applying Differential Thermal Analysis (DTA). The significant results in the direction of transition due to temperature are measured .in an entirely controlled manner The TGA Analysis of coal is performed on EXSTAR TG/DTA 6300 instrument at IIT Roorkee. The sample of weight 10.866 mg is heated upto 100° C by applying the rate of heating at 10° C per minute. Both reference material as aluminium powder and the sample of coal are heated at the same rate.

Figure 3.6, 3.7 shows the TGA/DTA curve for coal sample (1) and (2). The degradation of particles occurs in the range of 400 to 440° C and 400 to 479° C for coal sample (1) and (2). The moisture content in both the coals decreases in the temperature zone of 100 to 300° C and light volatile matter is seen in the temperature range of 100 to 300° C. There is another zone followed by preliminary zone is active pyrolysis and oxidation zone of range 300 to 500° C. The total degradation is observed to be 48.29% and 56.75% in coal sample (1) and (2) respectively. The maximum change in weight is observed at temperature of 500° C. The cause of less dehydration after temperature 500° C is known that porosity decreases at higher temperature. TGA curve analyses the loss of water taking place with the increase of temperature. From the TGA curve for coal, we come to the conclusion that as the temperature increases and reaches at 400° C, suddenly the loss of water increases and that goes on rising steeply with the increasing temperature upto the temperature of 500° C. The process of dehydration completes after passing on the temperature of 500° C

**Table 3.1 Classification of particle size on the basis of size**

<b>Powder Categories</b>	<b>Particle median size in microns</b>
Very coarse	Greater than 1000
Coarse	355-1000
Moderately Fine	180-355
Fine	125-180
Very Fine	90-125

**Table 3.2 Particle size distribution analysis of coal samples**

<b>Particle size (<math>\mu\text{m}</math>)</b>	<b>% Finer</b>	
	<b>Coal (1)</b>	<b>Coal (2)</b>
500	100.00	100.00
355	100.00	97.87
250	98.08	91.64
150	83.73	73.79
106	67.02	50.28
75	42.66	28.11
53	13.89	3.89

**Table 3.3 Elemental and compound composition of Coal (2)**

<b>Element</b>	<b>Weight%</b>	<b>Atomic%</b>	<b>Formula</b>	<b>Compound %</b>
C	27.03	33.10	CO <sub>2</sub>	99.03
Al	0.24	0.13	Al <sub>2</sub> O <sub>3</sub>	0.46
Si	0.24	0.12	SiO <sub>2</sub>	0.51
O	72.49	66.64		
Totals	100.00			

**Table 3.4 Physical properties of Coal (2)**

Specific gravity (g/cc)	2.32
Bulk density (g/cc)	0.91
Water holding capacity (%)	70.00
Porosity (%)	60.68
Plasticity	Non-plastic

**Table 3.5 Proximate Analysis of Coal samples**

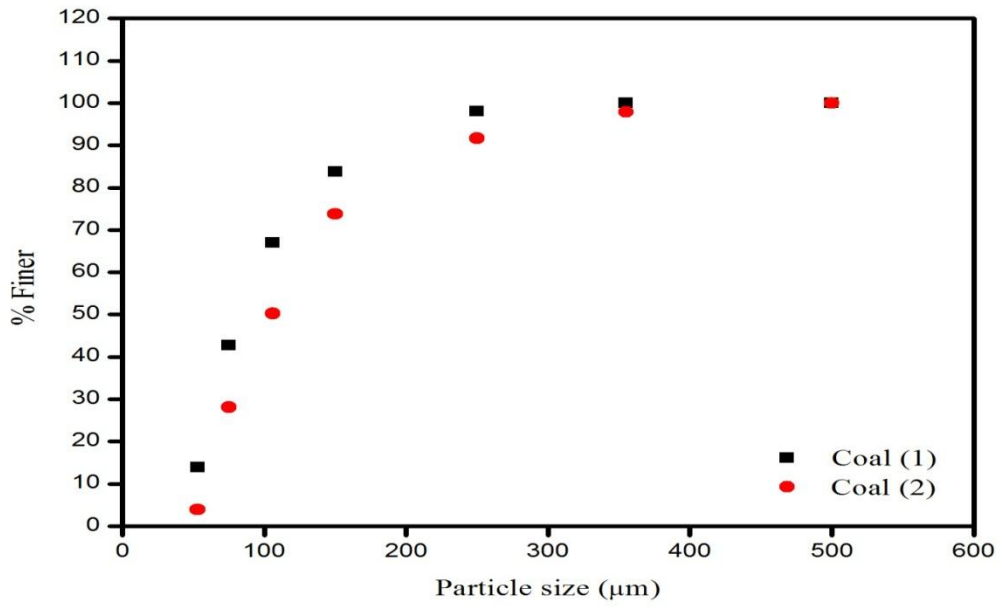
<b>Parameters</b>	<b>Coal (1)</b>	<b>Coal (2)</b>
Moisture Content %	5.39	3.53
Ash Content %	28.79	30.29
Volatile Matter %	23.89	16.74
Fixed Carbon % [100-(Moisture Content%+ Ash %+ V.M. %)]	41.93	49.44

**Table 3.6 Ultimate Analyses of Coal**

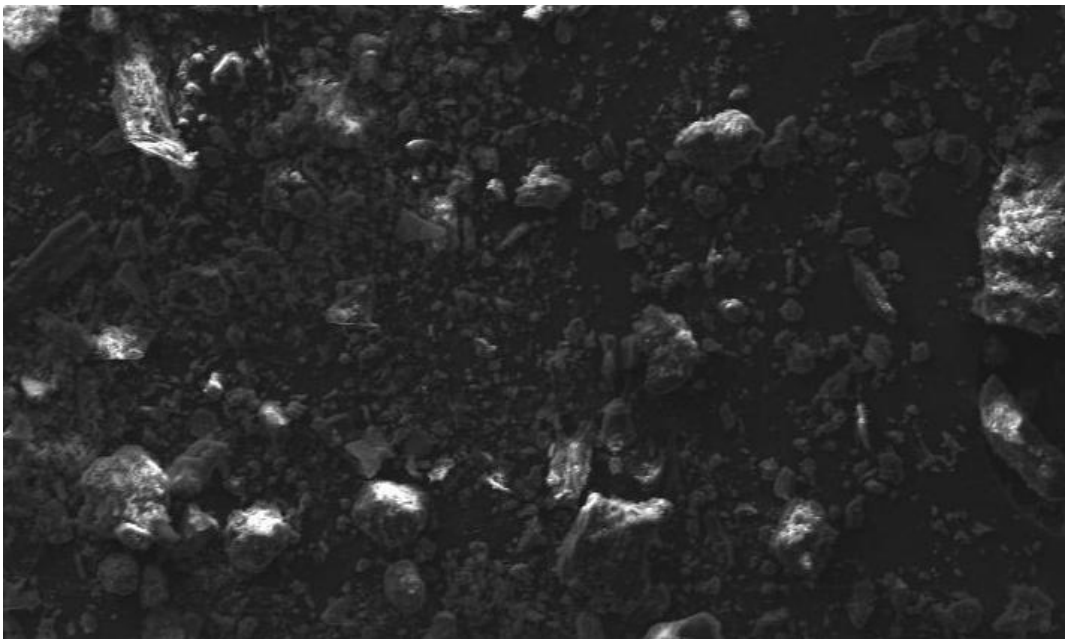
<b>Ultimate Analysis of Coal (2)</b>	
Weight (mg)	2.00
Protein Factor	6.25
Humidity %	0.00
C %	44.37
N %	1.05
H %	3.03
S %	0.39
O % [100-(C%+H%+S%+N %)]	51.16

**Table 3.7 pH analyses of Coal samples**

<b>Solids concentration by weight, %</b>	<b>Coal (1)</b>	<b>Coal (2)</b>
30	6.09	6.16
40	6.06	6.11
50	6.04	6.07
60	5.95	5.97



**Figure 3.1 Particle size distribution analyses of Coal samples**



**Figure 3.2 Scanning electron microscopy image of coal (1)**

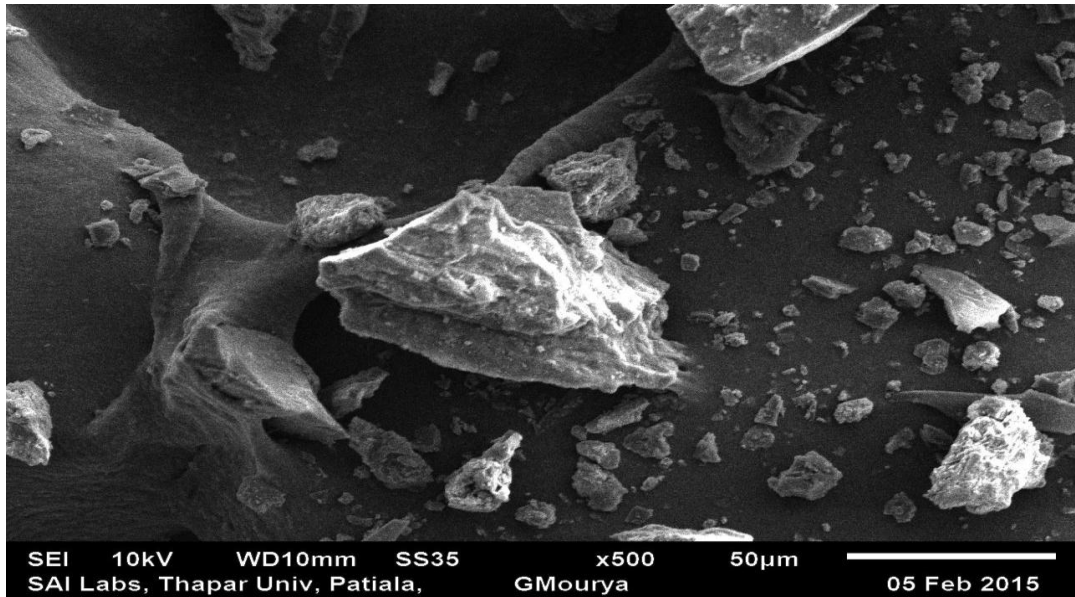


Figure 3.3 Scanning electron microscopy image of coal (2)

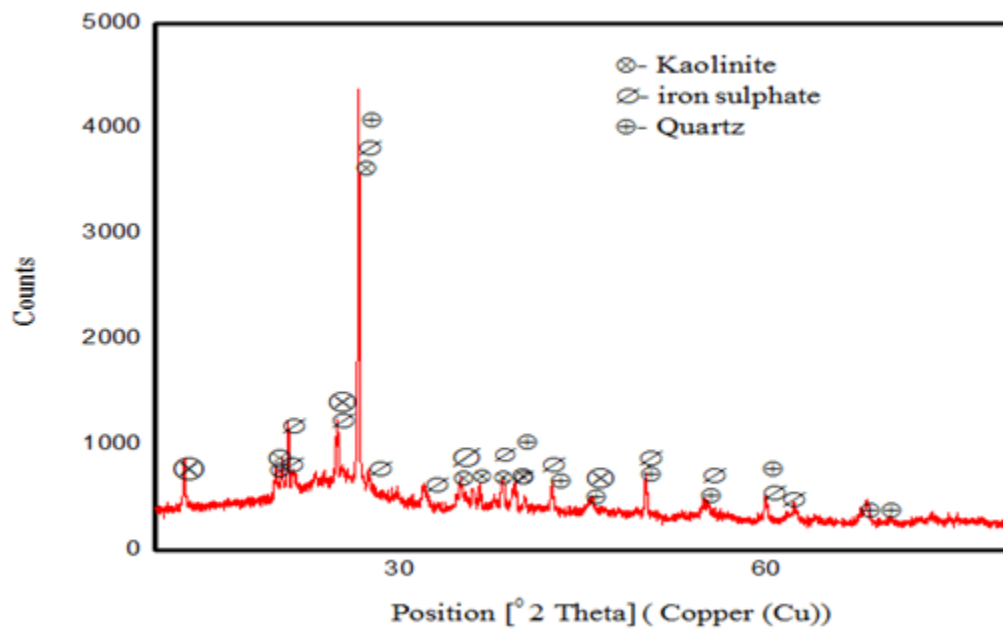


Figure 3.4 X-ray diffraction graph of coal (2)

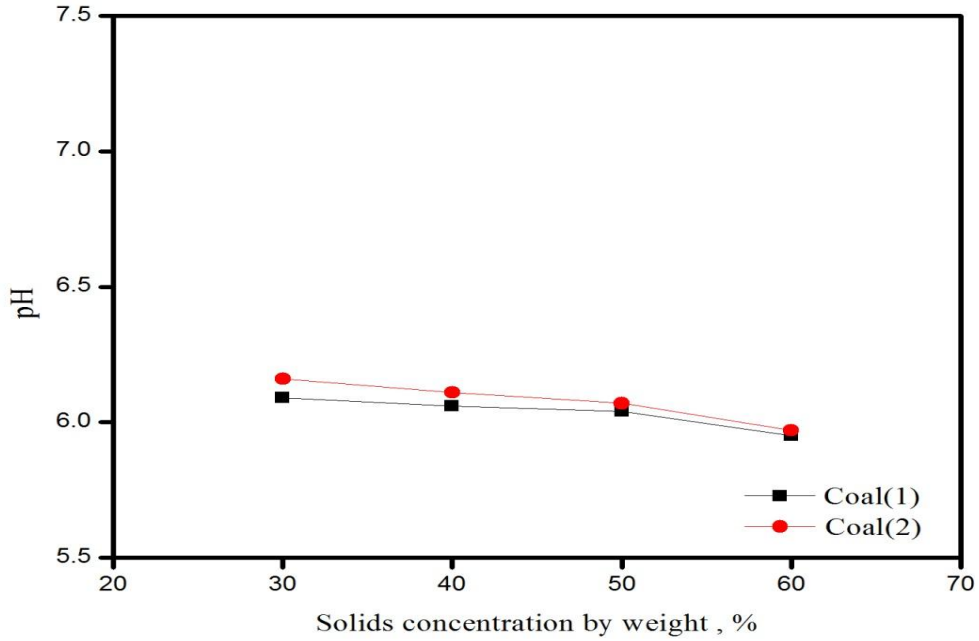


Figure 3.5 pH analyses of coal samples

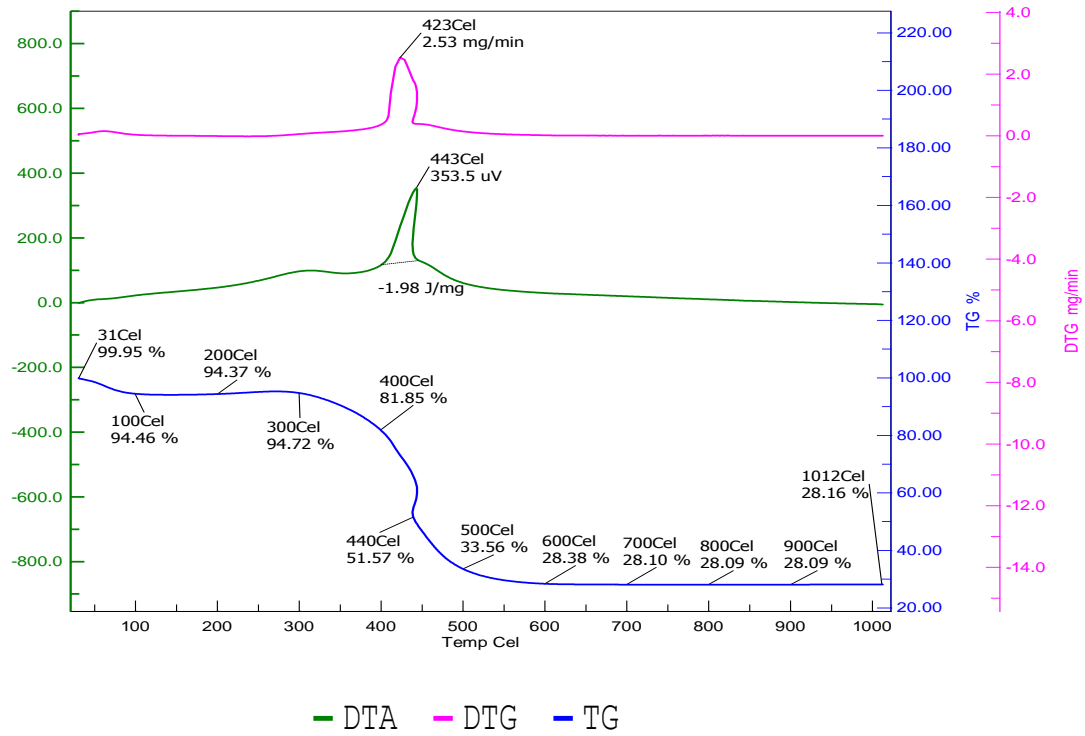


Figure 3.6 TGA, DTA and DTG curves of coal (1)

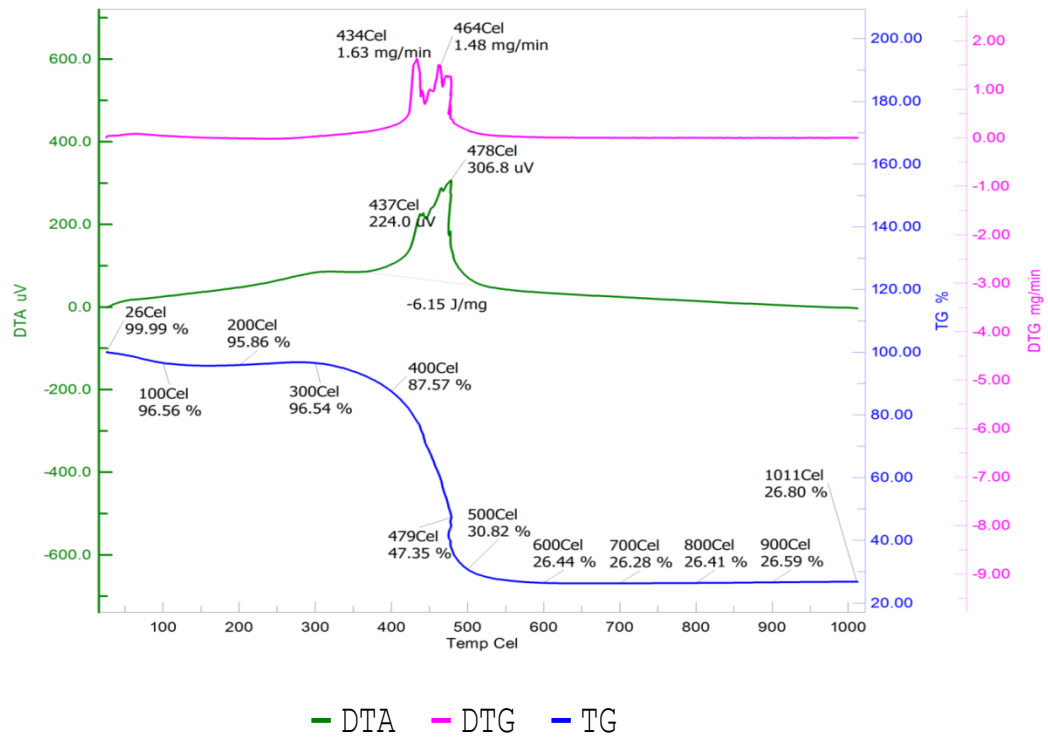


Figure 3.7 TGA, DTA and DTG curves of coal (2)

## **CHAPTER 4**

# **EXPERIMENTAL STUDY OF SLURRY FLOW THROUGH PIPELINE**

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The design criterion of pipeline mainly depends upon the major as well as minor head loss, quantity of slurry, size of the particle, viscosity of slurry etc. The pressure drop being measured at different locations in the pipeline, drastically affects by the presence of solid particles forming homogenous or heterogeneous suspension with the carrier fluid.

The presence of fine particles upto 30% concentration in carrier fluid shows up the Newtonian behaviour while flowing through the pipe loop. But, on the other hand, the slurry consisting of coarse particles to have needed of high velocity, results in more consumption of energy for a particular concentration of transportation of slurry. Most of the researchers studied for the either equisized or small size range of particles to predict the pressure drop experimentally. Thus, the main focus of the current study is to investigate the pressure drop characteristics of slurry, flowing through pipeline fittings like contraction and bends, in a pilot plant test loop. Most of the scholars believe that the flow through the local fittings is difficult to analyse in comparison to straight pipeline. Therefore, it is necessary to observe the pressure drop through local pipeline fittings for coal slurry at different concentrations with varying flow velocity.

### **4.1 DESCRIPTION OF PILOT PLANT TEST LOOP**

The schematic diagram of the test loop consisting of pipeline, Local fittings and many other types of equipment is shown in the figures. The pipe loop mainly consists of mild steel pipeline having pipe length of approximately 45 metre. This set up starts up with the pipe bend of diameter 101.6 mm connected to the hopper bottom by means of gate valve. The slurry is being prepared in the hopper bottom which is provided with the stirring arrangement to keep the slurry well mixed inside mixing tank during operation. Further, a T- junction is made. On one side of T-junction, a flush tank is connected to the main pipe line via T-section with the help of gate valve. The flush tank is needed to consider into account in order to prevent the pipe line from blockage during the slurry flow through pipe loop. The open impeller centrifugal slurry pump

having rated capacity of 50m<sup>3</sup>/hr is driven by means of 3 phase Sq Cage Induction Motor of capacity 7.5 HP. For continuous monitoring of the flow rate, a precalibrated electromagnetic flow meter is installed in the horizontal pipeline having dia. 101.6mm. The variation of flow rate is done with the help of plug valve which is located after the flow meter downstream the pipeline. The slurry after passing through pipe loop reaches back to the hopper bottom tank having capacity of around 0.8 m<sup>3</sup>. To measure the pressure drop of slurry flow along the pipeline differential pressure transducers are installed across pipe fittings which are essentially measuring the pressure difference at different locations namely along sudden contraction and bend of 50.8mm. Figure 4.1 shows The Schematic Diagram of the pilot plant test loop.

## 4.2 SPECIFICATION OF PILOT PLANT TEST LOOP

The specification of components and several measuring instruments used in the pilot plant test loop has been depicted in the below mentioned table.

**Table 4.1 Specification of pilot plant test loop**

<b>Open Impeller Centrifugal Slurry Pump</b>	
Capacity (m <sup>3</sup> /hr)	50
Head (m/c)	15
Motor (HP)	7.5
Pump Speed (RPM)	1460
<b>3 Phase Sq. Cage Induction Motor</b>	
Voltage (Volts)	420
KW/HP	5.5/7.5
RPM	1460
<b>Stirrer Motor</b>	
RPM	1425
HP/KW	1/0.75
Volts	220/230
<b>Electromagnetic Flow Meter</b>	
Rated capacity (m <sup>3</sup> /hr)	50

Maximum Temperature (° C)	90
Size (mm)	100
Accuracy	(+/- 0.5)
<b>Gauge Pressure Transducer</b>	
Range (Bar)	100
Output (mA)	4-20
Accuracy	(+/- 0.5) Fs
<b>Differential Pressure Transducer</b>	
Calibration (KPa)	0.5-10
Supply (DC Voltage)	12-45
<b>Pipeline</b>	
4 inches pipe line length	Approx.892 inches
2 inches pipe line length	Approx. 860 inches
<b>Valves</b>	
Plug Valve (1)	4 inches ID
Gate Valve (1)	4 inches
Gate Valve (1)	2 inches
<b>Elbows</b>	
Elbow (4)	4 inches
4 inches elbow radius	10 inches
Elbow (2)	2 inches
2 inches elbow radius	5 inches
T-joint (1)	4 inches
<b>Tank Capacity</b>	
Hopper Bottom (Slurry Preparation Tank )	800 ltrs.
Flush Tank	645 ltrs

### 4.3 PROCEDURE OF PIPELINE TRANSPORTATION

Firstly, before conducting the experiment of coal slurry flowing through the pipe loop, the experiment on water flow through pipe loop was conducted for several times in order to get the pressure difference between two sections placed at 2 metres apart along a straight pipe of diameter 50.8mm. The measured pressure difference is converted into corresponding head loss for water flow through a pipeline and the friction factor is calculated using the Darcy equation. Then, a known quantity of water approximately 0.495 m<sup>3</sup> was put in the storage tank and coal powder having an amount of 5 Kg added up into the mixing tank in order to prepare the slurry of 1% solids concentration by weight. The slurry was mixed well with water with the help of stirrer. As soon as the slurry observed to be well mixed with water obtaining a desired condition of concentration, the slurry was flown through the pipe loop. The centrifugal slurry pump is used to impart the energy to slurry so that the motion can takes place in pipe when the valve will open. The flow meter has been installed at the pipe to measure the discharge and the differential pressure transducer has been installed at the transition of pipe to measure the pressure difference between the two points. The experiment has been conducted for different discharge. Similarly the experiment was repeated for different concentrations of 3%, 7% and 10%. The concentration of solid by weight in slurry is defined as:

$$C_w = \frac{W_s}{W_s + W_w} \quad (4.1)$$

At a particular concentration of solid by weight the pressure drops were measured across different pipe fittings such as at sudden contraction and bends. Also the pressure transducers are placed at inlet and outlet points. While the slurry was flowing through pipe loop, it was kept on running at full speed of pump and corresponding to this velocity the pressure drop was measured, in subsequent runs the discharge was reduced using a valve. The density of slurry is calculated by employing the following relationship as follows:

$$\rho_m = \frac{100}{\frac{C_w}{\rho_s} + [100 - C_w]/\rho_L} \quad (4.2)$$

The pressure drops across pipe fittings i.e. at sudden contraction and bend diameter as 50.8 mm and radius 127 mm with the particle size of less than 100 $\mu$ m of coal slurry were measured. The concentration of solids by weight was varied at 3%, 7% and 10%. The flow velocity was also kept on varying corresponding to different discharges of 10, 18, 22, 26, 29 and 39m<sup>3</sup>/hr. Thus the head losses were measured for coal slurry flow through pipe with varying velocity at low concentration.

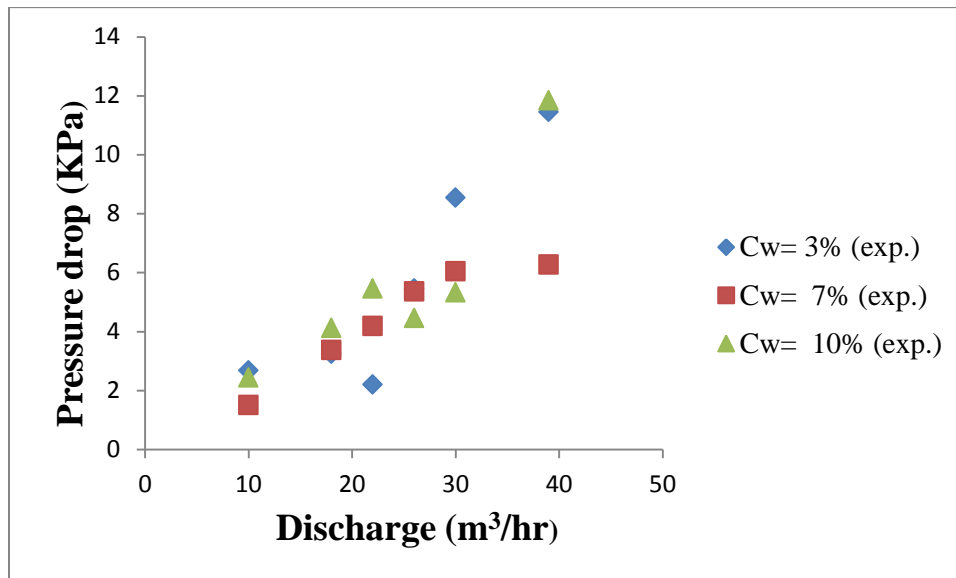
#### **4.4 MEASURING INSTRUMENTS AND DEVICES USED**

- **Electromagnetic Flow meter** it is a most common flow meter coming after the differential and positive displacement flow meters. A magnetic field is applied to the metering tube, which results in a potential difference proportional to the flow velocity perpendicular to the flux lines. The physical principle at work is electromagnetic induction. The magnetic flow meter requires a conducting fluid, for example, water that contains ions, and an electrical insulating pipe surface, for example, a rubber-lined steel tube.
- **Pressure sensor** this is useful in measuring the pressure of liquid or gases. It is an expression of the force required to stop a fluid from expanding, it is usually the force per unit area. A Pressure sensor commonly acts as a transducer; it generates a signal as a function of the imposed parameter. This signal generally comes in the electric form.
- **Open Impeller centrifugal slurry Pump** The impeller is not provided with any shroud. These pumps are used in dredgers and elsewhere for handling mixtures of water, sand, pebbles and clay in which the solid contents may be as high as one part in four. The impeller has very rough duty to perform. Its life in some cases ranges from 500 to 1000 hours.

## 4.5 EXPERIMENTAL RESULTS

### 4.5.1 Pressure drop across sudden contraction in pilot plant test loop

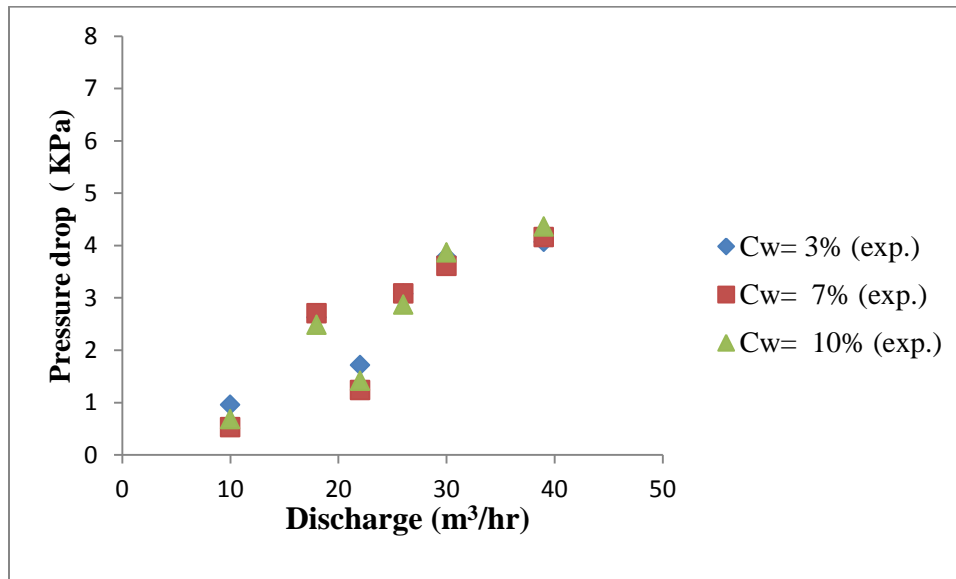
The pressure drop for coal water mixture flowing through sudden contraction at 3%, 7% and 10% solids concentration by weight with different values of discharge i.e. 10, 18, 22, 26, 29 and 39m<sup>3</sup>/hr is observed. Fig 4.2 shows the variation of pressure drop with the variation of discharge for the 3%, 7% and 10% concentration of coal slurry. It is found from fig 4.2 that as the discharge increases the pressure drop also increases. It is also found from Fig 4.2 that the pressure drop increases with increase in concentration of coal slurry. The rate of increase of pressure drop at given solid concentration is found to be higher at higher velocity. The increase in density as well as viscosity with increasing input concentration might be the reason of increasing the pressure drop across sudden contraction of pipe.



**Figure 4.2 Experimental investigation of pressure drop across sudden contraction geometry**

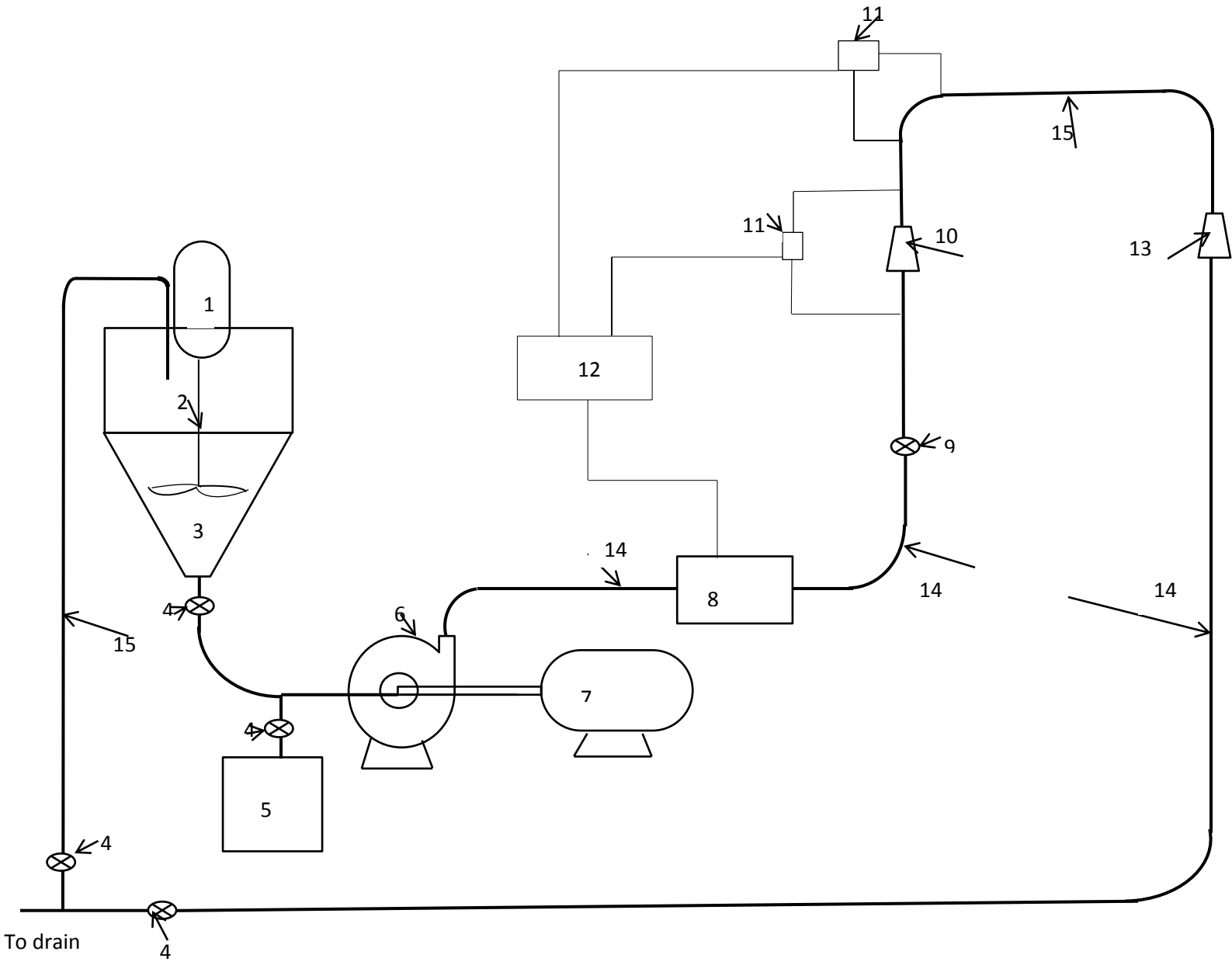
#### 4.5.2 Pressure drop across pipe bend in pilot plant test loop

The pressure drop characteristics for coal water slurry flowing through bend has been investigated by conducting experiment on pilot plant test loop. The experiment is conducted by varying the flow rates from 10 m<sup>3</sup>/hr to 39 m<sup>3</sup>/hr for different solids concentrations of the coal slurry flowing through pipe bend and the pressure drop is measured by using the differential pressure transducer installed in the pipe bend. Fig 4.3 shows the variation of pressure drop with the variation of discharge for the 3%, 7% and 10% concentration of coal slurry. It is found from fig 4.3 that as the discharge increases the pressure drop also increases similar to the sudden contraction of pipe. It is also found from Fig 4.3 that the pressure drop increases with increase in concentration of coal slurry. In both the cases of sudden contraction as well as the pipe bend, the general trends of increasing pressure drop with increasing flow rate and increasing pressure drop with increase in slurry concentration were observed for all flow rates and concentrations.



**Figure 4.3** Experimental investigation of pressure drop across pipe bend geometry

Figure 4.1 shows the pilot plant test loop. It is concluded that the pressure drop for coal slurry finds to increase with the increase of input concentration as well as flow rates in both the geometries as mentioned in many literatures.



- |                            |  |                               |
|----------------------------|--|-------------------------------|
| 1. Stirrer Motor           | 6. Open Impeller Centrifugal slurry Pump | 11. Diff. Pressure Transducer |
| 2. Stirrer                 | 7. 3 Phase Sq. Cage Induction Motor      | 12. Data Logger               |
| 3. Slurry Preparation Tank | 8. Electromagnetic Flow Meter            | 13. Sudden Expansion          |
| 4. Gate Valve              | 9. Plug Valve                            | 14. 102 mm N.B. Pipe          |
| 5. Flush Tank              | 10. Sudden Contraction                   | 15. 51mm N.B. Pipe            |

**Figure 4.1 Schematic Diagram of Pilot Plant Test Loop**

## CHAPTER 5

### NUMERICAL ANALYSIS

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#### 5.1 INTRODUCTION

Computational fluid dynamics (CFD) is called to be one of the branches of fluid mechanics where the numerical methods are taken into account to solve the governing flow equation to determine the flow behaviour. There are few applications such as lift and drag phenomena in vehicles aerodynamics, ships hydrodynamics, in turbo machinery as flow through diffusers etc. where the CFD tool is used in an efficient manner to analyse the flow behaviour. Today, the extent of CFD is being seen in the field of multiphase flow through different geometries. The flow behaviour of multiphase fluid is analysed by adopting either of the following approaches i.e. Euler- Lagrange approach and Euler- Euler approach. The Euler- Lagrange approach involves two phases i.e. fluid phase and dispersed phase. When the particle- particle interactions are neglected, the technique is considered to be a simple technique for analysing the multiphase flow. The Navier-stokes equations are generally used to analyse the fluid phase in this approach. While, basic conservation equations are used to analyse the fluid flow behaviour in Euler- Euler approach.

#### 5.2 GOVERNING EQUATIONS

The governing equations can be of two forms i.e. conservation form and non-conservation form. These equations used for the analysis of three dimensional, steady turbulent flow through a pipe network can be given as below.

- **Continuity equation**

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \quad (5.1)$$

- **Momentum equation**

$$\frac{Du}{Dt} = X - \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\mu}{\rho} \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad 5.2 (a)$$

$$\frac{Dv}{Dt} = Y - \frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{\mu}{\rho} \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \quad 5.2 (b)$$

$$\frac{Dw}{Dt} = Z - \frac{1}{\rho} \frac{\partial p}{\partial z} + \frac{\mu}{\rho} \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \quad 5.2 (c)$$

- **Navier- stokes equation in conservation form for non-newtonian fluid**

$$\begin{aligned} \frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} &= \frac{-\partial p}{\partial x} + \frac{\partial}{\partial x} \left( \gamma \nabla \cdot V + 2 \mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left[ \mu \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right] + \\ \frac{\partial}{\partial z} \left[ \mu \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \right] + \rho f_x & \end{aligned} \quad (5.3)$$

- **K- $\omega$  SST model**

- k- Equation**

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u)}{\partial x} + \frac{\partial}{\partial x} \left[ \left( \mu + \frac{\mu_t}{\rho_k} \right) \frac{\partial k}{\partial x} \right] + G_k + G_b - \rho \epsilon - Y_m + S_k \quad 5.3(a)$$

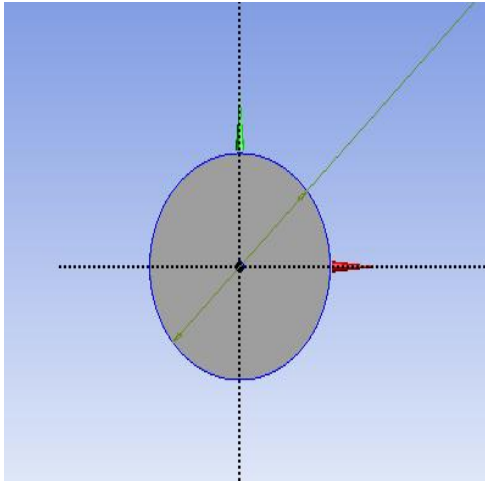
- $\omega$ - Equation**

$$\frac{\partial(\rho k \omega)}{\partial t} + \text{div} (\rho k \omega U) = \text{div} \left[ \frac{\mu_t}{\sigma_\epsilon} \text{grad} (k \omega) \right] + C_{1\epsilon} \frac{(k \omega)}{k} 2 \mu_t E_{ij} \cdot E_{ij} - C_{2\epsilon} \rho \frac{(k \omega)^2}{k} \quad (b)$$

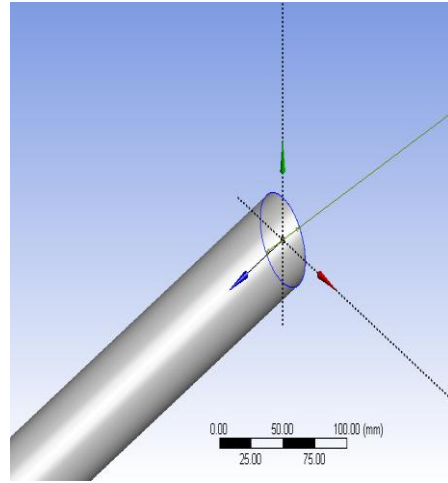
The terms  $\text{div} (\rho k \omega U)$  and  $\text{div} \left[ \frac{\mu_t}{\sigma_\epsilon} \text{grad} (k \omega) \right]$  signifies the convective transport and diffusive transport phenomena occurring during the flow of fluid through conduit. Its application is seen in flows having separation, unconfined flows, rotating flows etc.

## 5.3 MODELLING AND MESHING

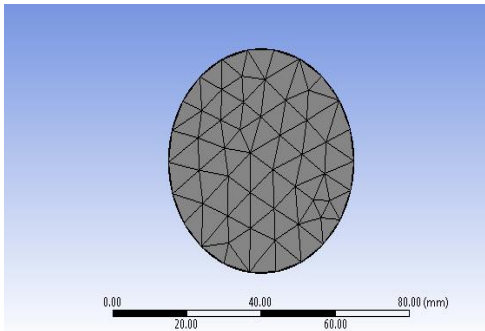
The straight pipeline geometry consisting of pipe diameter and length to be 50mm and 2m is made in ANSYS Design Modeller 14.8. The length of pipe is taken sufficiently long so that the fully developed condition can be maintained after the fluid travels some distance along the pipeline. Figure 5.1(a), (b) shows the cross sectional view and the Isometric view of pipeline respectively. The domain was discretised into 103995 mesh elements using tetrahedron mesh having 7 mm mesh element size. The skewness and orthogonal quality of mesh element size 7mm were observed to be 0.798 and 0.233 respectively that characterized the good quality mesh. The different zones are named for the entire domain as inlet, outlet and wall.



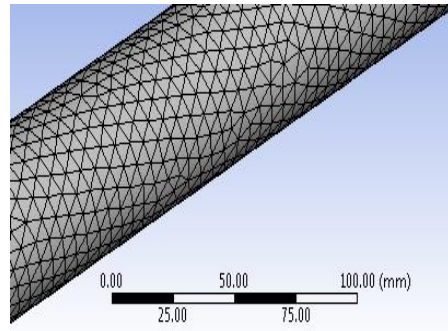
**Figure 5.1 (a) Cross sectional view of pipe**



**Figure 5.1 (b) Isometric view of pipe**



**Figure 5.2 (a) 7 mm mesh along cross section**



**Figure 5.2 (b) 7mm mesh along the length**

#### **5.4 BOUNDARY CONDITONS**

These are the number of conditions being applied on the geometry.

At inlet	Velocity inlet, Uniform velocity is assumed
At wall	Shear condition- no slip, wall motion to be stationary, roughness constant and height to be 0.5 and 0.
At outlet	Pressure outlet, Gauge pressure to be zero.

## 5.5 NUMERICAL SOLUTION

The SIMPLE scheme under pressure velocity coupling was utilized to solve the single phase flows. Under relaxation factor for pressure, momentum, turbulent kinetic energy, turbulent dissipation rate and turbulent viscosity are taken to be 0.3, 0.7, 0.8, 0.8 and 1 respectively. Convergence criterion was set to be  $10^{-3}$ . To analyse the multiphase flow through pipe, Eulerian model as a multiphase model and SST K- $\omega$  model as a mixture model were used. The Eulerian model is generally adopted to analyse particle- laden flows. First order upwind scheme is used to discretise the momentum, volume fraction, turbulent kinetic energy and specific dissipation rate equation. Standard wall function is used to make the computation expense being least. Phase- Coupled SIMPLE algorithm under pressure velocity coupling is used to analyse the flow behaviour of multiphase fluid as coal slurry flows through pipeline. As the fluid is incompressible and separation occurs in the pipeline, to take care of these concepts, the pressure based solver is used.

### **GRID INDEPENDENCY TEST:**

The grid independence test was performed on straight pipeline to check the change in results with changing mesh size. Initially the domain of straight pipe line was discretized into 70778 elements by using the tetrahedral mesh of size 8 mm and the Pressure drop is simulated using Eq. 5.1-5.3. The percentages of change in results are checked making the grid finer. The mesh size was changed uniformly throughout the domain from 8 mm to 4 mm by decreasing of 1 mm making finer grid and the pressure drop is simulated using Eq. 5.1-5.3. Table 5.1 shows the grid independence test and it is found that there is no significant change in the simulated pressure drop below 7 mm of mesh size having 103995 elements. Figure 5.2(a) and 5.2(b) shows the mesh size of 7mm for straight pipeline.

**Table 5.1 Grid independence test**

<b>Mesh size (mm)</b>	<b>No. of elements</b>	<b>Mesh element type</b>	<b>Variation in results</b>
8	70778	Tetrahedron	yes
7	103995	Tetrahedron	no
6	163708	Tetrahedron	no
5	282049	Tetrahedron	no
4	548937	Tetrahedron	no

After selecting the mesh size for domain, five different turbulence models namely K- $\epsilon$  standard, K- $\epsilon$  Realizable, K- $\epsilon$  RNG, K- $\omega$  standard and K- $\omega$  SST were applied to test which model results are coming near to the theoretical calculation of pressure drop for water flow through pipeline of given dimensions. While applying the turbulence models, the flow velocity was taken as 1.5 m/sec. The percentage error of pressure drop by simulation with theoretical result for five different turbulence models, namely, K- $\epsilon$  standard, K- $\epsilon$  Realizable, K- $\epsilon$  RNG, K- $\omega$  standard and K- $\omega$  SST was observed as 15.062%,14.198%,15.679%, 10% and 8.148% respectively. Out of these turbulence models, the K- $\omega$  SST model finds to be the most appropriate model for calculating the pressure drop characteristics of the fluid flowing through pipeline.

## **5.6 VALIDATION OF RESULTS**

### **5.6.1 Pressure drop prediction across straight pipe**

The simulation results of pressure drop for flow of water through straight pipeline at different mesh element size were compared with theoretical calculation for water by applying the Darcy-Weisbach equation in order to find the percentage error between the simulation and the theoretical calculation. The flow velocity of 1.5 m/sec and K- $\omega$  SST model was taken to simulate the pressure drop characteristics. It was observed that the numerically investigated pressure drop results for water at the mesh size of 7mm and mesh elements 103995 are lying much closer to the theoretical results. Hence, the flow of coal slurry through pipe network was simulated using K- $\omega$

SST model and 7mm mesh size. Table 5.2 shows the simulation results of pressure drop in straight pipeline.

### 5.6.2 Pressure drop prediction across pipe bend

- **Problem set up**

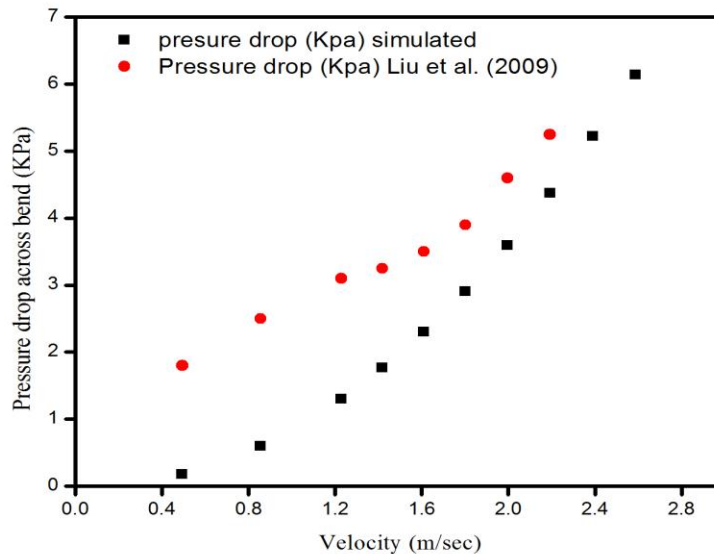
The experiment has been conducted by Liu et al. (2009) to determine the pressure drop for the coal slurry flow through bend by employing bend of diameter 50mm and  $R_c/D$  (bend radius to diameter ratio) 1.5 at 57% solids concentration by weight of coal slurry with particle size of 134.55  $\mu\text{m}$  and flow velocity in the range of 0.1515 to 2.5877 m/sec. The simulation results of pressure drop for the coal slurry flowing through a bend are compared with the experimental results given by Liu et al. (2009). Table 5.3 shows the physical and rheological properties of coal slurry at solid concentration by weight of 57 % considered by Liu et al. (2009). The present study used the same data considered by Liu et al. (2009) for simulating the flow of coal slurry through pipe bend. The Eulerian model as a multiphase model and SST K-omega as a viscous model for coal water mixture have been chosen to simulate the flow of coal slurry through given geometry.

**Table 5.2 Physical and rheological properties of coal water slurry (Liu et al. (2009))**

1.	Coal density (g/cc)	1.187		
2.	Solids concentration by weight, % (% $C_w$ )	57		
3.	Average diameter of particle ( $\mu\text{m}$ )	134.55		
4.	$Re_g$ (Reynolds number)	100-1200		
5.	Rheological properties			
$C_w$ % (by wt.)	Power- law model parameters		Temperature °C	Shear rate
	k	n		
57	0.0678	1.07	25	270-2500

- **Results and discussions:**

Figure 5.3 shows the comparison of computed result of pressure drop with experimental results of pressure drop with varying velocity of coal slurry across pipe bend. It is observed that the behaviour of computed pressure drop is same as in experimental results. The magnitudes of pressure drop are in good agreement with experimental data at higher velocities but there is a little deviation at smaller velocities.



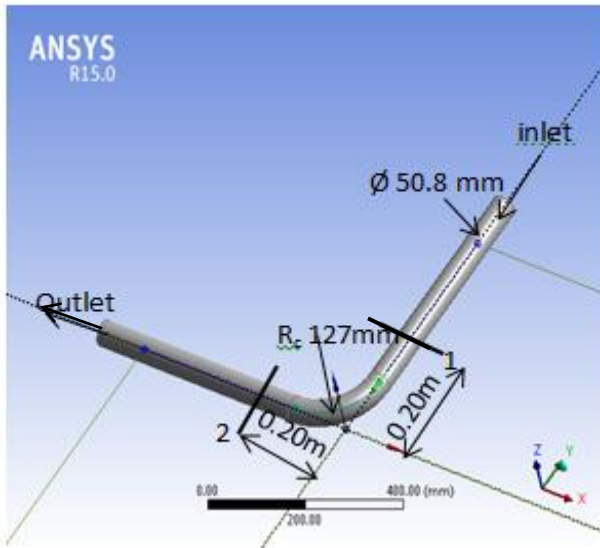
**Figure 5.3 Comparison between simulated pressure drop and experimental pressure drop for bend (Liu et al. (2009))**

## **5.7 SIMULATION OF PRESSURE DROP ACROSS PIPE FITTINGS**

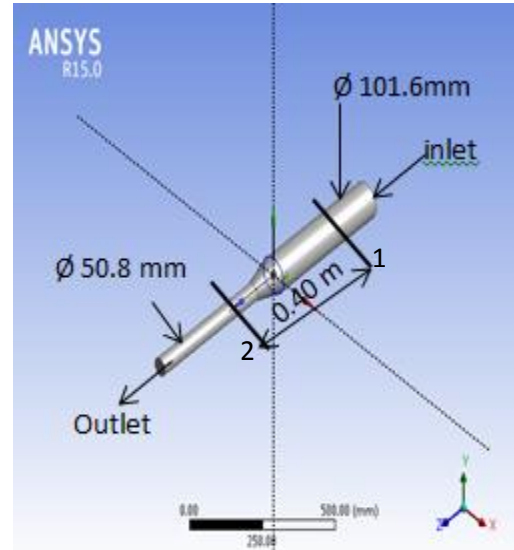
### **5.7.1 Modelling and Meshing**

In present study the CFD approach has been adopted to study the pressure drop characteristics of coal water slurry flow through local pipe fittings i.e. pipe bend and sudden contraction at different concentrations of solid by weight i.e. 40%, 50% and 60% with varying flow rate or velocity corresponding to different flow rates as 10, 18, 22, 26, 29 and 39 m<sup>3</sup>/hr. The experimental study of coal water mixture flow through pipe loop at low concentration has been discussed in the previous chapter but for the further study of flow behaviour at high

concentration inside pipe loop, the CFD code ANSYS FLUENT 15.0 has been adopted. ANSYS Design Modeller (DM) is used to make the geometry of pipe bend and sudden contraction. Figure 5.4, 5.5 shows the geometry of pipe bend and sudden contraction constructed in ANSYS V 15.0 with their dimensions.

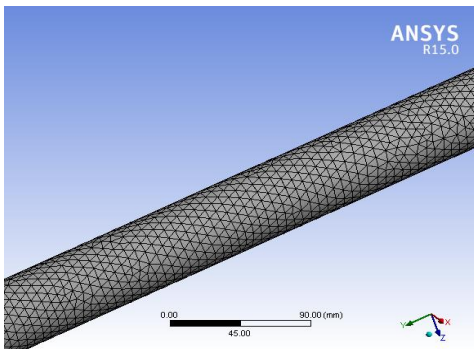


**Figure 5.4 Geometry of pipe bend**

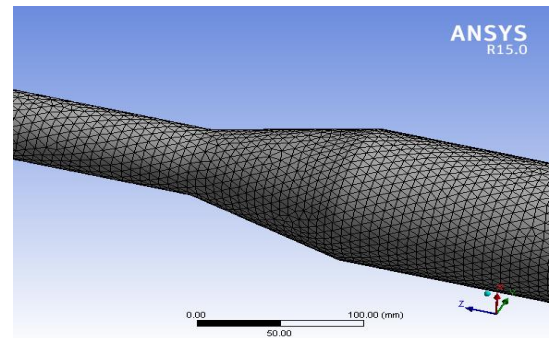


**Figure 5.5 Geometry of sudden contraction**

The models of both fittings i.e. sudden contraction and bend were discretised into 60757 and 131145 mesh elements respectively using tetrahedron coarse mesh of 7mm size in ANSYS R15.0 tool. The skewness quality of bend and sudden contraction geometries is observed to be 0.758 and 0.750 which characterizes the good quality mesh. Figure 5.6,5.7 shows the meshing of local pipe fittings with 7mm mesh element size.



**Figure 5.6 Meshing of bend**



**Figure 5.7 Meshing of sudden contraction**

### 5.7.2 Properties of coal material

The various physical and rheological properties needed for the simulation of coal slurry through pipe line are given in below mentioned Table 5.4.

**Table 5.3 Physical and rheological properties of coal slurry through pipe loop**

1.	<b>Coal specific gravity (g/cc)</b>	2.32		
2.	<b>Average diameter of particle (<math>\mu\text{m}</math>)</b>	100		
3.	<b>Solids concentration by weight, %, (% <math>C_w</math>)</b>	40%, 50%, 60%		
4.	<b>Rate of discharge (<math>\text{m}^3/\text{hr}</math>)</b>	10,18,22,26,29 and 39		
<b>Rheology of coal slurry at different solids concentration (Kumar, 2014)</b>				
	<b>Temperature (<math>^{\circ}\text{C}</math>)</b>	<b><math>C_w</math> (%)</b>	<b>Shear rate (1/s)</b>	<b>Apparent viscosity (pa.s)</b>
	30	40	600	0.043
	30	50	600	0.053
	30	60	600	0.227

### 5.7.3 Boundary conditions

These conditions are necessary to take into account before simulating the flow behaviour of multiphase fluid involving these time only two fluids through pipeline.

**Table 5.4 Boundary conditions for multiphase flows through pipeline**

<b>Position /Phases</b>	<b>Phase 1 (Water)</b>	<b>Phase 2 ( Coal)</b>
<b>At inlet</b>	Constant uniform velocity normal to boundary.	Constant uniform velocity and volume fraction of solid.
<b>At outlet</b>	Pressure outlet to be zero gauge pressure for the mixture.	
<b>At wall</b>	No slip condition for both the phases as well as for mixture and roughness constant and height to be 0.5 and 0.	

#### 5.7.4 Solving procedure of multiphase flow (coal slurry flow) using FLUENT

These are the input parameters used for simulating the fluid behaviour through pipeline. Table 5.6 shows the solving procedure built up by using FLUENT.

**Table 5.5 Solution table of fluent for simulating mutiphase flow through pipeline**

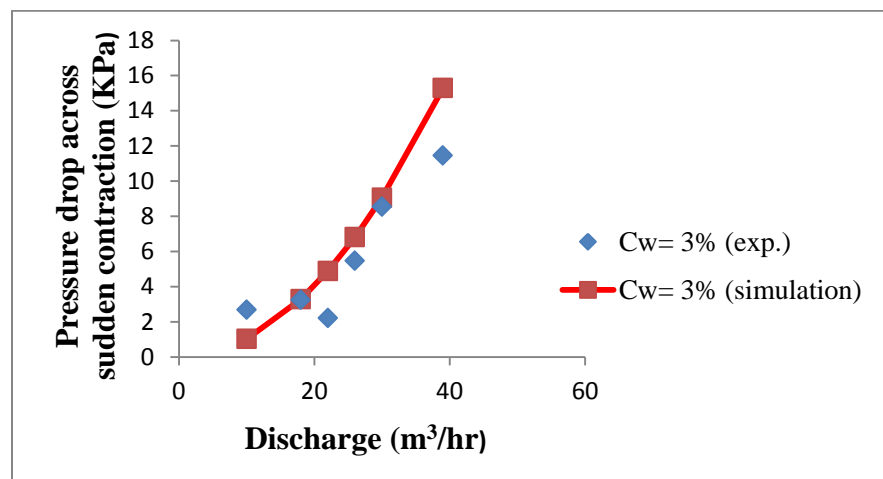
<b>Solution set up</b>	
<b>Model</b>	Eulerian model (multiphase model), no. of eulerian phases- 2 SST K- $\omega$ (viscous model), mixture ( turbulence multiphase model)
<b>Materials</b>	Coal (density, viscosity input parameters)      Water (density, viscosity input parameters)
<b>Phases</b>	Water (primary phase)      Coal (secondary phase) Particle diameter (input paramete) Ganular viscosity in kg/m-s (Syamlal—oberian) Granular bulk viscosity in kg/m-s (Lun et al)
<b>Boundary conditions</b>	Described earlier in table 5.5 for both the phases
<b>Solution methods</b>	Phase coupled SIMPLE scheme under pressure-velocity coupling scheme First order upwind scheme for momentum under spatial discretization First order upwind scheme for volume fraction First order upwind scheme for turbulent kinetic energy and dissipation rate.
<b>Solution controls</b>	Under relaxation factor for pressure , density, momentum and turbulent viscosity to be 0.3, 1,0.7 and 1 respectively.

The simulation of coal water slurry flow through pipeline has been carried out using the eulerian two phase as a multiphase and k- $\omega$  sst as a viscous model. The governing equations from equation 5.1 to 5.3 along with boundary conditions as mentioned in table 5.5 were used to compute the results of pressure drop for coal water slurry flow at high concentration. The convergence criterion for continuity, momentum and energy was chosen as  $10^{-3}$  to simulate the flow behaviour of fluid. The rheology data mentioned in Table 5.4 is used for simulating the coal slurry at different solids concentration of 40%, 50% and 60%.

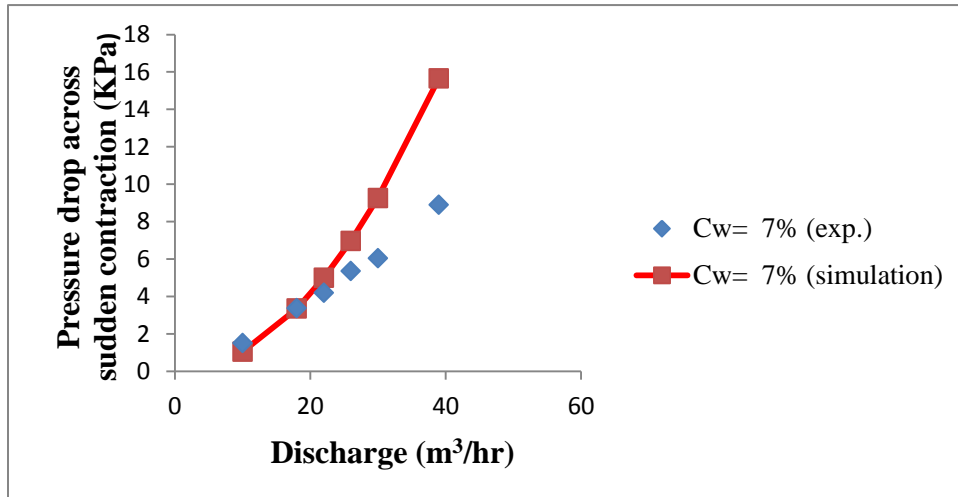
## 5.8 SIMULATION RESULTS AND DISCUSSIONS

### 5.8.1 Pressure drop prediction across Sudden contraction

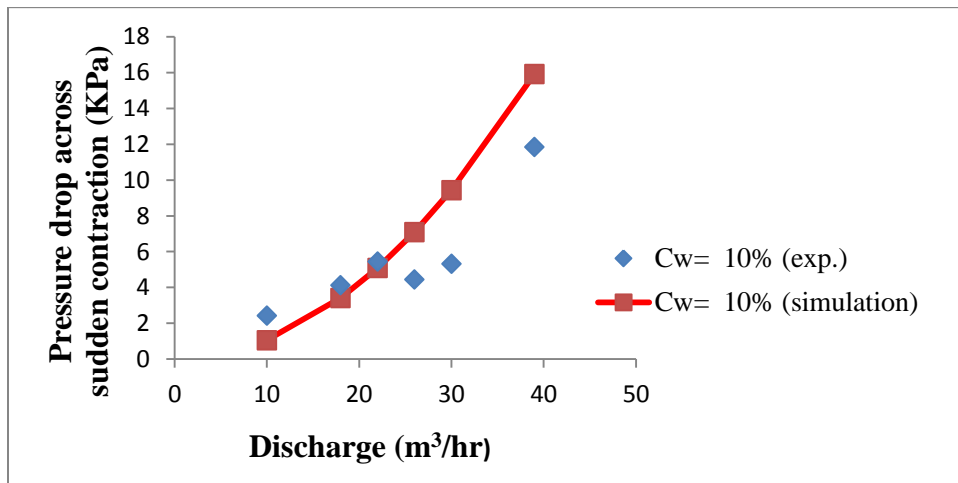
The coal water slurry flow through sudden contraction geometry at different concentrations of 3%, 7% , 10%, 40%, 50% and 60% with varying flow rates from 10 m<sup>3</sup>/hr to 39 m<sup>3</sup>/hr was simulated numerically for the determination of pressure drop. The simulation results of pressure drop for coal water slurry at concentrations 3%, 7% and 10% are compared with experimental results. As the fluid shows newtonian behaviour upto 30% concentration of solids, the mixture viscosity at different concentrations needed for simulating the flow behaviour is assumed to be same as that of water. Figure 5.8 (a), (b) and (c) shows the comparison of numerical results of pressure drop for coal slurry flow through sudden contraction at 3%, 7% and 10% concentration with experimental results and it is found that the numerical results are in good agreement with the experimental results. The increasing trend of pressure drop with increase in slurry concentration as well as with increase in discharge is found in numerical simulation.



**Figure 5.8 (a) Comparison of simulation with experimental at 3% concentration for sudden contraction**



**Figure 5.8 (b) Comparison of simulation with experimental at 7% concentration for sudden contraction**



**Figure 5.8 (c) Comparison of simulation with experimental at 10% concentration for sudden contraction**

From the Figure 5.8 (a), (b) and (c), it can be concluded that there is a little deviation between experimental and numerical results.

### 5.8.2 Pressure drop prediction across pipe bend

The coal slurry flowing through pipe bend at different conditions of concentrations and flow rate is also simulated to determine the pressure drop. The simulation results were compared with experimental results of pressure drop in order to predict the deviation between these two data. Figure 5.9 (a), (b) and (c) shows the comparison between the experimental data and simulation data for coal slurry flow.

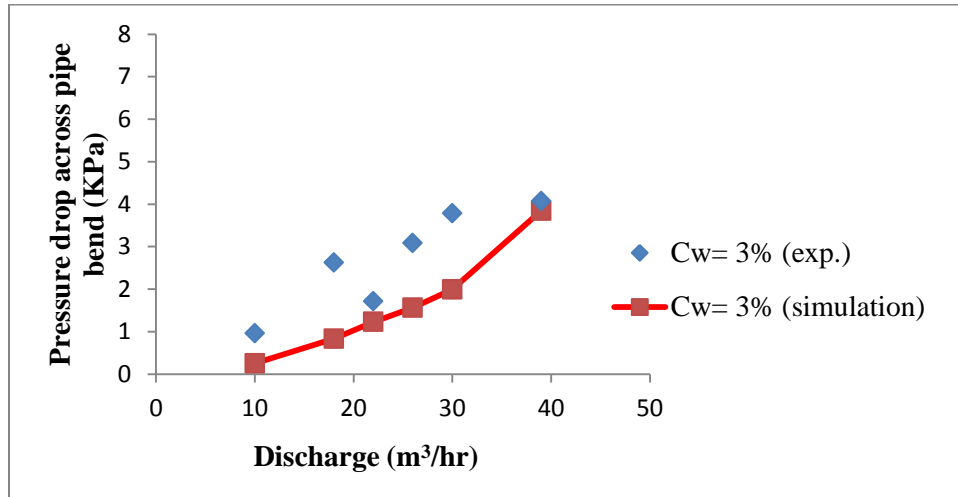


Figure 5.9 (a) Comparison of simulation with experimental at 3% concentration for bend

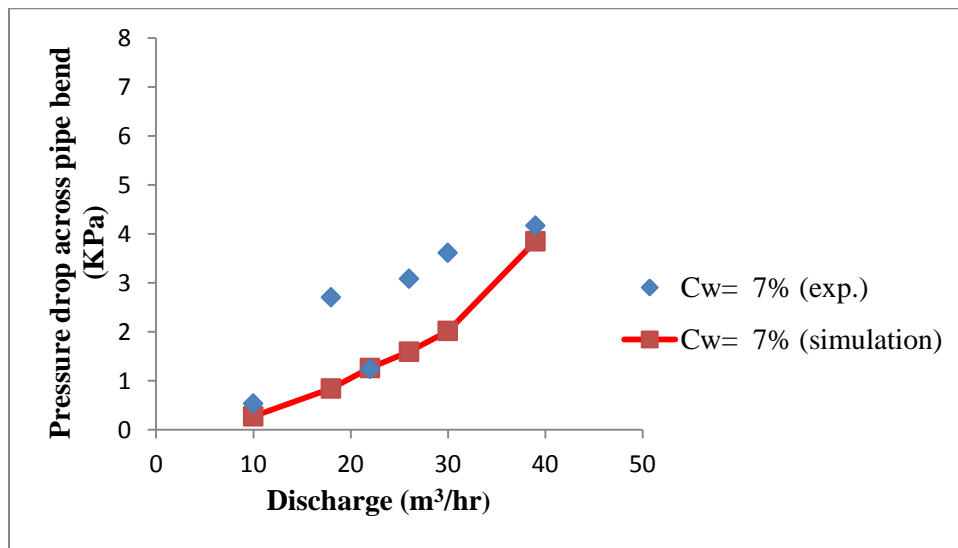
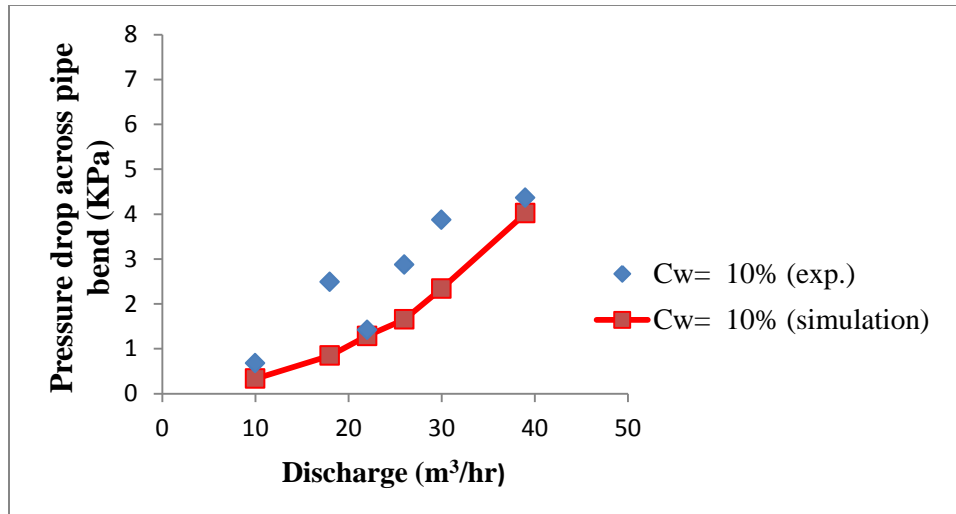


Figure 5.9 (b) Comparison of simulation with experimental at 7% concentration for bend

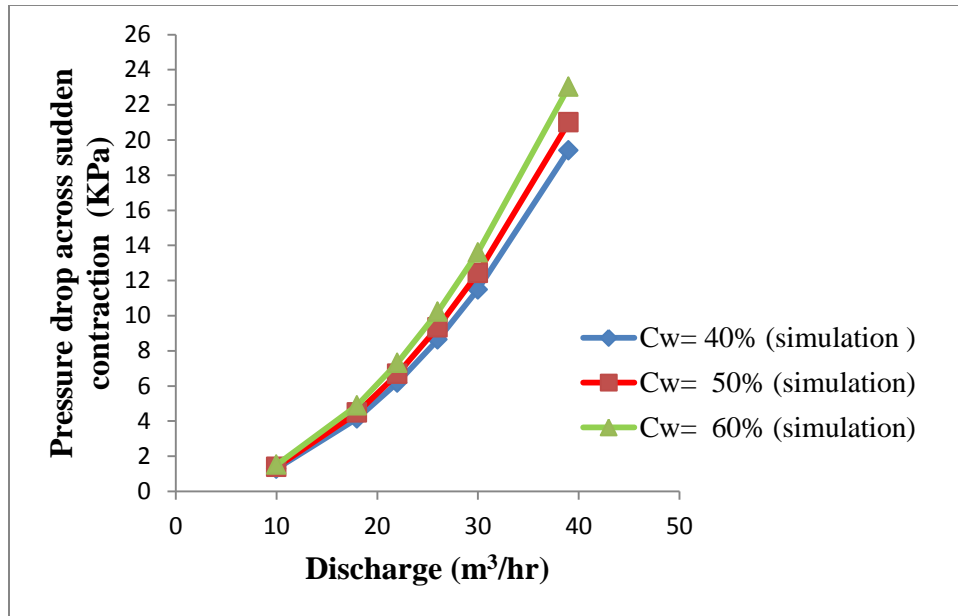


**Figure 5.9 (c) Comparison of simulation with experimental at 10% concentration for bend**

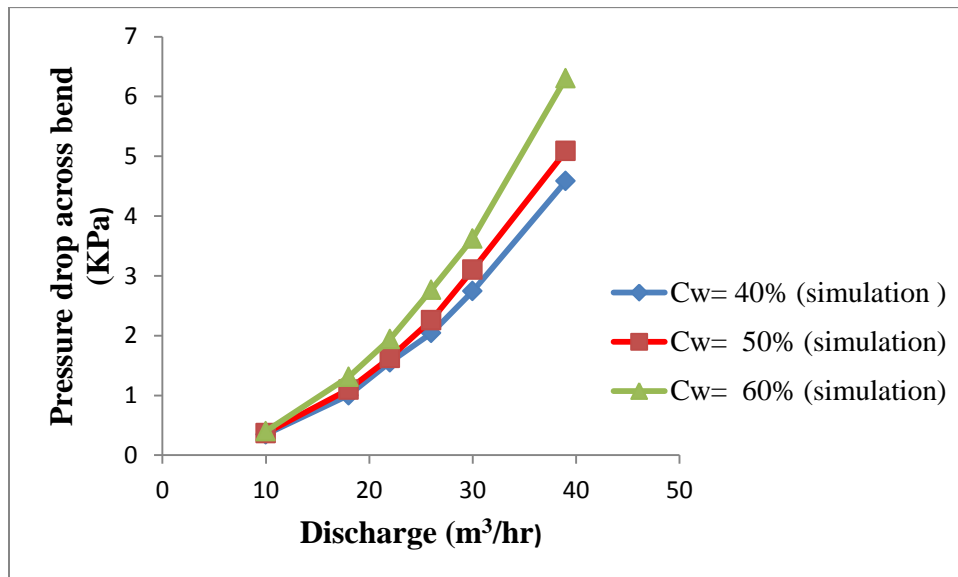
From the Figures 5.9 (a), (b) and (c) , it is observed that the predicted pressure drop at higher velocity for slurry flow through pipe bend shows a very less deviation for all the concentrations but in the flow rates values from 18 to 30 m<sup>3</sup>/hr , the deviation is found to be large in magnitude.

### **5.8.3 Pressure drop prediction across Sudden contraction and pipe bend for coal slurry at high conc.**

The pressure drop is also predicted for higher concentration of coal water slurry numerically. The high concentration of 40 %, 50% and 60 % flowing through the sudden contraction as well as in pipe bend is simulated numerically to predict the pressure drop. The flow rate was taken same as that in case of coal slurry flow at 3%, 7% and 10% solid concentration by weight. Table 5.3 shows the physical and chemical properties of slurry for different concentration which is used for numerical simulation. Figure 5.10 (a), (b) shows the variations of pressure drop for coal water mixture flowing through sudden contraction and pipe bend geometry at high concentration respectively. From the Figures 5.10 (a) and (b), it can be concluded that the rate of increase of pressure drop at higher flow rate for different concentrations is higher because of the abnormal increase of viscosity. The general trends were observed in both the geometries. More friction is observed generally at higher velocity which results in higher pressure drop.



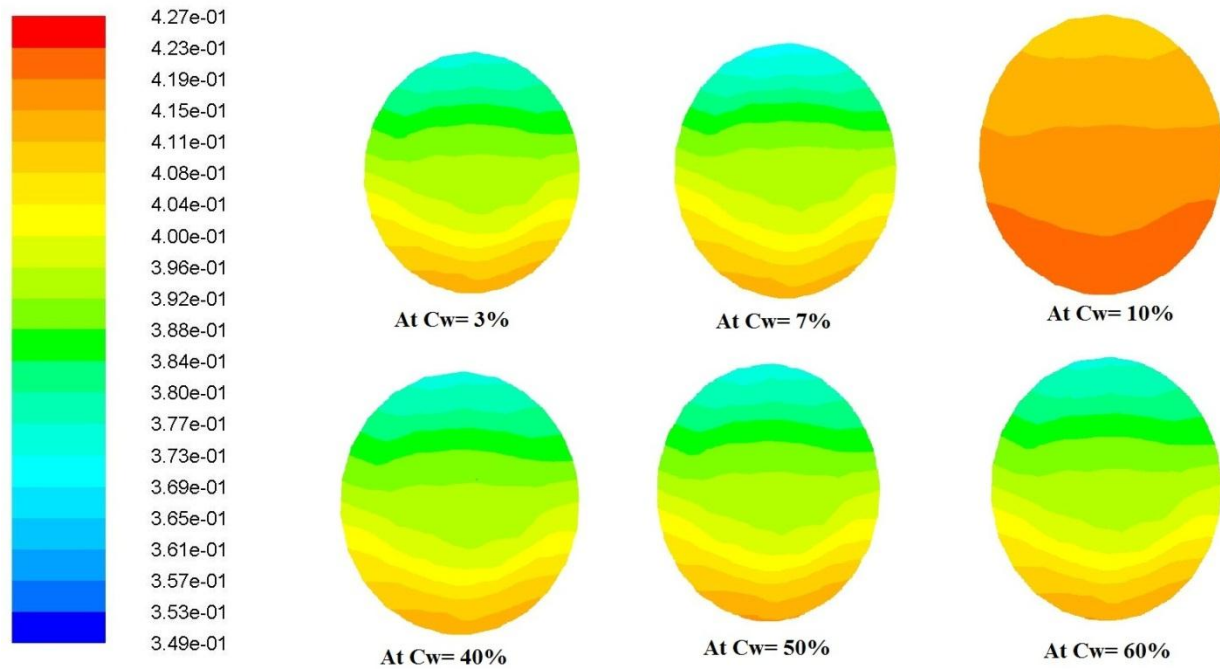
**Figure 5.10 (a) Pressure drop prediction for coal water mixture flowing through sudden contraction at high conc.**



**Figure 5.10 (b) Pressure drop prediction for coal water mixture flowing through bend at high conc.**

### 5.8.4 Volume fraction profile

The volume fraction profile is determined at the outlet of the pipe bend for different concentrations of coal slurry for the discharge of  $10 \text{ m}^3/\text{hr}$ . The finer particles generally show a homogeneous suspension with water. As the solid concentration increases, the rate of settlement increases. Figure 5.11 shows the volume fraction profile at outlet with varying solids concentration considered for the discharge of  $10 \text{ m}^3/\text{hr}$ .

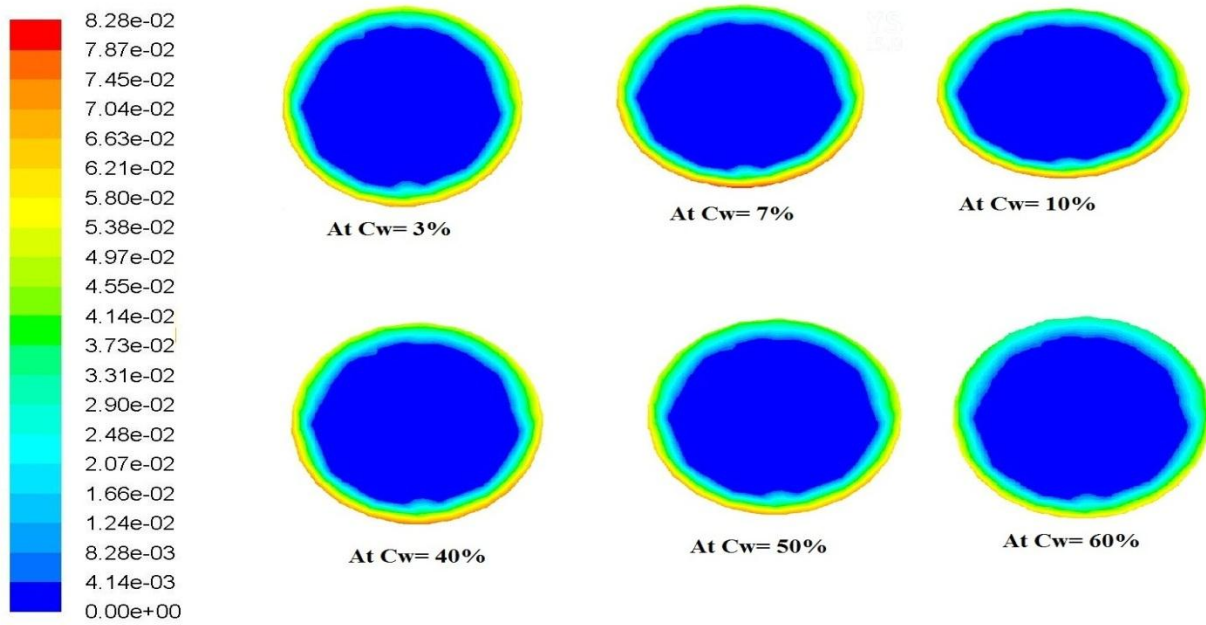


**Figure 5.11 Volume fraction profile of coal slurry with varying solids concentrations flowing at a uniform velocity in bend**

### 5.8.5 Wall shear stress profile

The shear stress acts on coal slurry during its motion through pipe geometry which affects its hydraulic gradient characteristics. Figure 5.12 shows the shear stress profile at outlet of bend for varying concentrations of solids considered at fixed velocity. As the concentration increases, the wall shear stress on coal slurry increases with it and that results in increase in viscosity and

which in turn increases the pressure drop. The wall shear stress for a 60% concentration is observed to be greater in magnitude .



**Figure 5.12 Wall shear stress profile at outlet of bend during coal slurry flowing with uniform velocity at varying solids concentrations**

## CHAPTER 6

### CONCLUSIONS AND FUTURE SCOPES

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#### 6.1 Conclusions

The experimentation on coal water slurry with low concentration at 3%, 7% and 10% flowing through pilot plant test loop is conducted in order to analyse the pressure drop at various pipe transitions i.e. sudden contraction and bend. For studying the coal slurry flow behaviour at high concentration, the commercially available software FLUENT software in CFD package is used to determine the pressure drop at sudden contraction and pipe bend. The simulation results of pressure drop at pipe fittings i.e. sudden contraction and pipe bend for low concentration slurry flow are compared with the experimental results. Then after, the following conclusions have been extracted out from these studies of analysing pressure drop.

1. The shape of the coal particles having size less than 75  $\mu\text{m}$  have been investigated with the help of SEM-EDS approach. Most of the coal particles are found to be irregular in shape which in turn increases the surface tension effect and keeps the particles suspending and forming a homogeneous mixture at high concentration.
2. The coal powder characteristics like porosity and water holding capacity are found to be very high which means the coal powder will be showing static settlement at higher concentration. To avoid the settling conditions of slurry flow through pipeline, the coal slurry needs to keep in motion at all the time.
3. The experimental work conducted for determining the pressure drop of coal water mixture at low concentrations of 3%, 4% and 5% is compared with the simulation results of pressure drop at same conditions of slurry. The simulation result of pressure drop for slurry flow through fittings shows a deviation upto 67% at lower velocity. The general increasing trends of pressure drop are observed for the slurry flow at high concentration

through pipe fittings but the rate of increase of pressure drop at higher velocity for various concentration of coal slurry is found to be higher.

## **6.2 Future scopes**

There are many works still need to be discussed in future. Some of these are shown as below:

1. Simulations of erosion wear for pilot plant test loop at different locations i.e. at pipe fittings.
2. Simulation of coal slurry to predict the pressure drop while flowing through a combination of geometries as straight pipeline attached with sudden contraction, then gradual expansion and so many more are in combination.
3. To modify the pilot plant test loop for determining the pressure difference between inlet and outlet section of pipe.

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